*The brain at the edge**

(it is all about un-co-ordination)

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Sailing somewhere in the Caribbean, March 2, 2010

"Per, to me the brain is critical"...

"Yes, for me too Dante!"

Kim Christensen, DRC, Per Bak, Oleg (Brookhaven National Lab. Circa 1990), Photo by Carmen Prado.

Bak (1996) How nature works;

Chialvo & Bak. (1997) eprint arXiv:adap-org/9707006

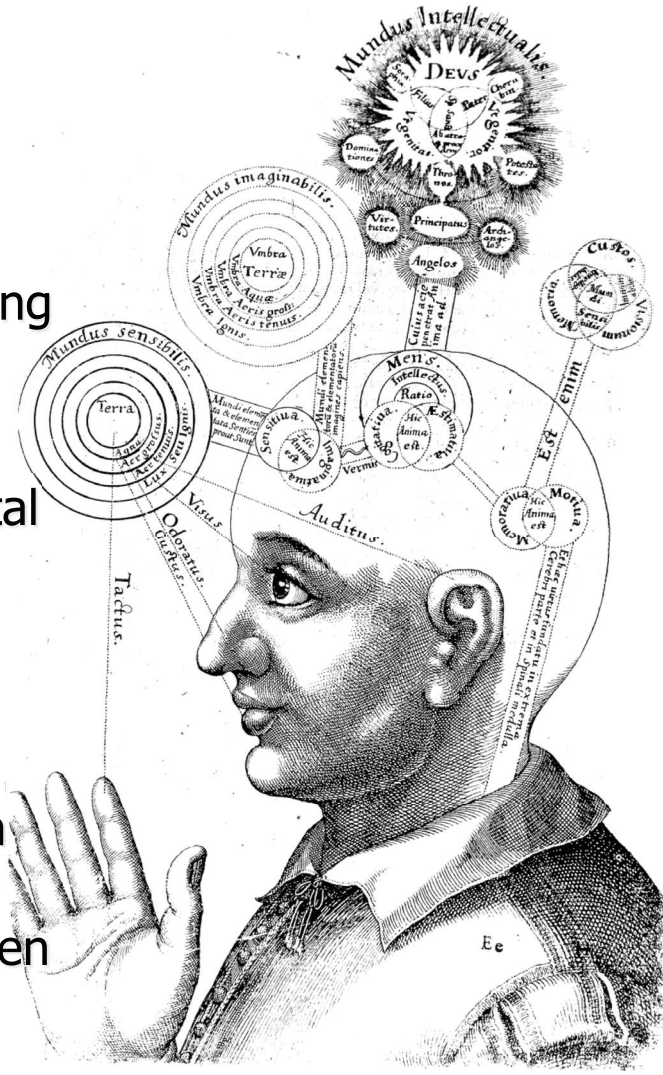
Points to be made:

1. The brain seems a relatively **small** dynamical system.
   (composed by a **few dozens** interacting areas)
2. It performs a **small** number of behaviors. (also about a **few dozens**)
3. Even "relatively small" dynamical systems posed near a (critical) second order phase transition, can **generate the largest variety of robust and flexible behavior.** (by using the abundance of metastable states at criticality)
4. The claim we are making is that some of the **most fundamental properties** of the functioning brain are possible just because **it stays at the border** of such instability.

We review the motivation, the arguments and some recent results as well as the implications of this view of the functioning brain

Motivation and Blah Blah

- Almost all interesting macroscopic phenomena, from gravity to fotosintesis from superconductivity to muscle contraction are all product of an underlying collective phenomena
- Science is often seen as explaining a phenomena at *one level* from fundamental laws at *another level*



- The brain is not an exception, we explain behavior (what we see) in terms of the underlying collective (often partially hidden to us)

Collectives: A few conflictive demands ...

As a collective the brain have a few conflictive demands:

"Integrated" AND "segregated" dilema (Edelman,Sporns,Tononi, etc).

This "dilema" is probably not unique of brains but generic of complex systems.

Q: how different is this conflict from being spontaneously posed at a phase transition in between order and disorder?

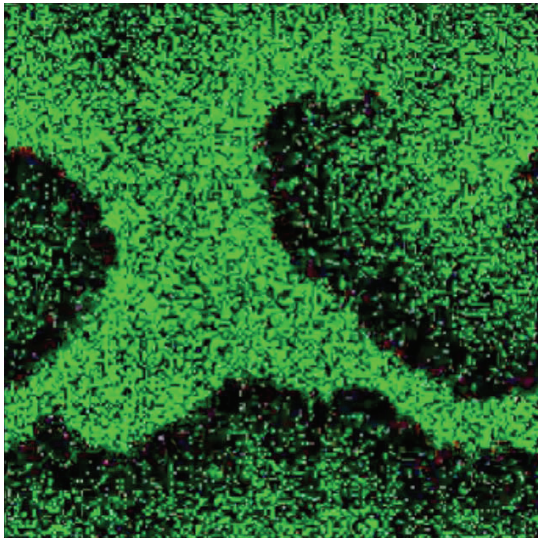
Most recent guerrilla (aka: "Collaborators")

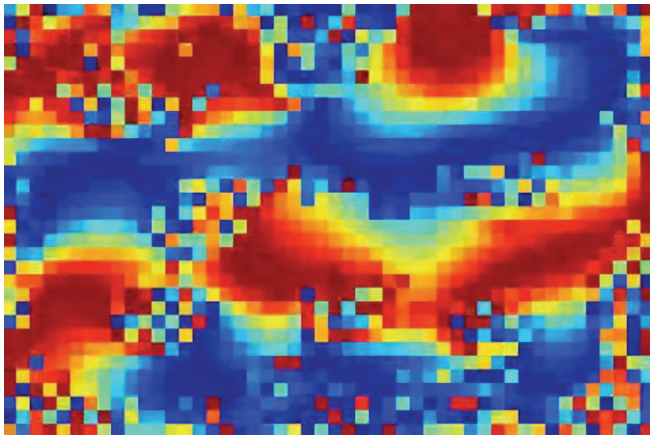
On large-scale brain dynamics:
Pablo Balenzuela (Physics, UBA, Buenos Aires); Daniel Fraiman (Math, UdeSA, Buenos Aires); Maximino Aldana (Physics, UNAM, Cuernavaca, Mexico); Paul Expert, K. Christensen , H. Jensen, et al. (Imperial College, UK).

On avalanches:
In vivo: Tiago Ribeiro, Mauro Copelli (Physics, Recife, Brazil); Sidarta Ribeiro (Neuroscience, Natal, Brazil).
In vitro: Dietmar Plenz (NIMH, USA).
In silico: S. Cannas, F. Tamarit, Physics, Cordoba, Argentina); Hans Herrmann (ETH, Zurich); Lucilla de Arcangelis (Physics, Napoli)

On behavior:
Mauro Copelli (Physics, Recife, Brazil); Celia Anteneodo (Physics, PUC, Rio, Brazil).

On potential clinical implications:
Pedro Montoya (University of Islas Baleares, Palma de Mallorca, Spain)
Hugo Berra (Universidad Nacional de Rosario, Rosario, Argentina, www.cimaprofisio.net)

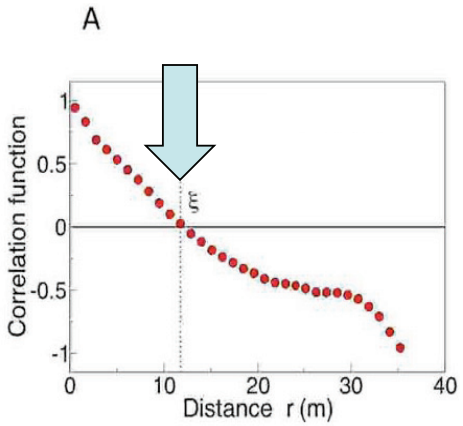


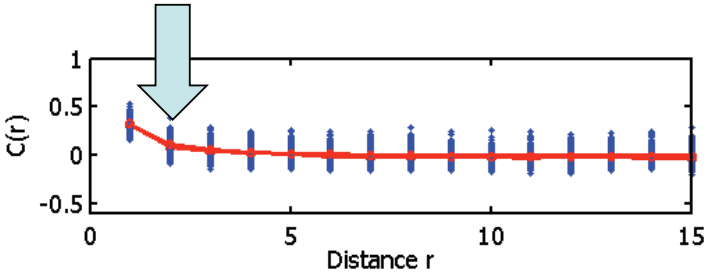


What is common in the dynamics of these spatiotemporal patterns?

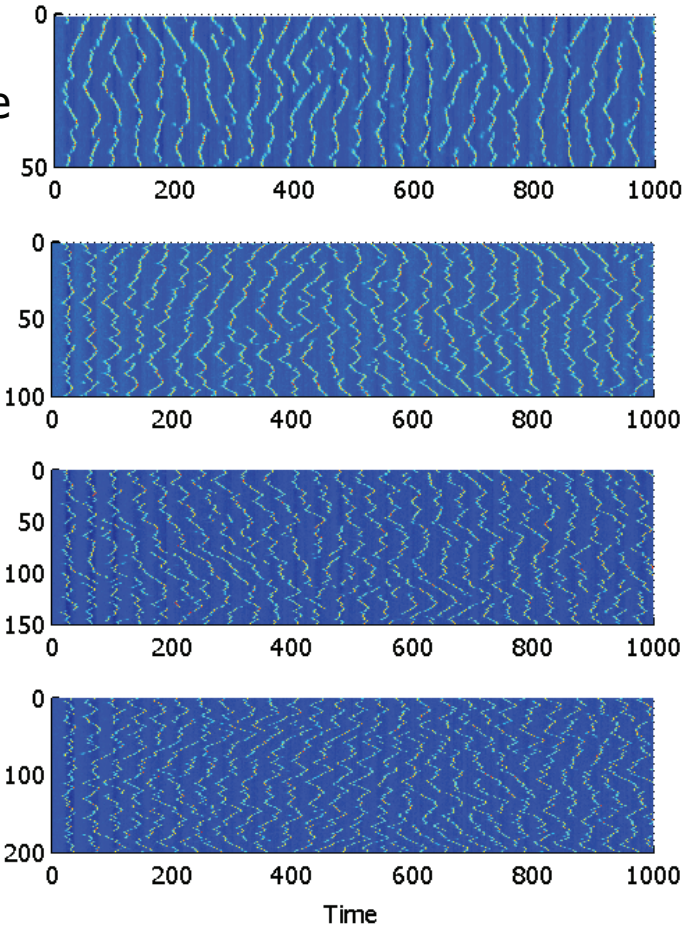
The presence of a characteristic scale (i.e., the wavelength)

Example of a system with finite correlation ξ length (independent of system's size)

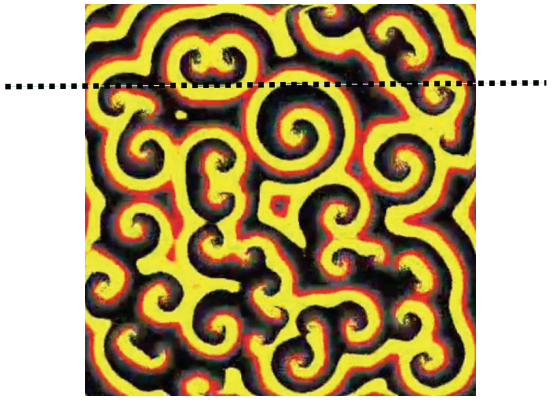


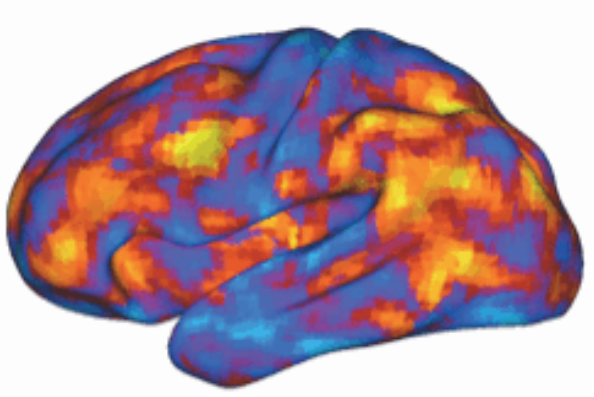


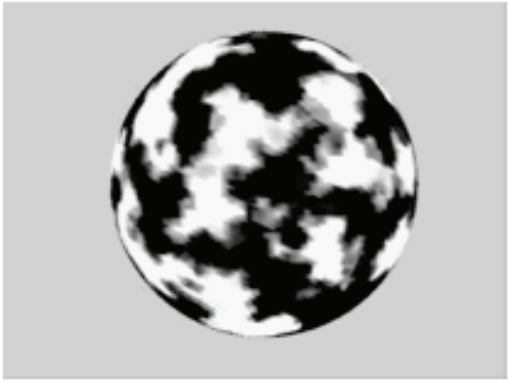
System Size increases



Compute the correlation length ξ for increasing system's size: It is a constant







What is common in the dynamics of these spatiotemporal patterns?

The lack of a characteristic scale (more precisely defined latter)

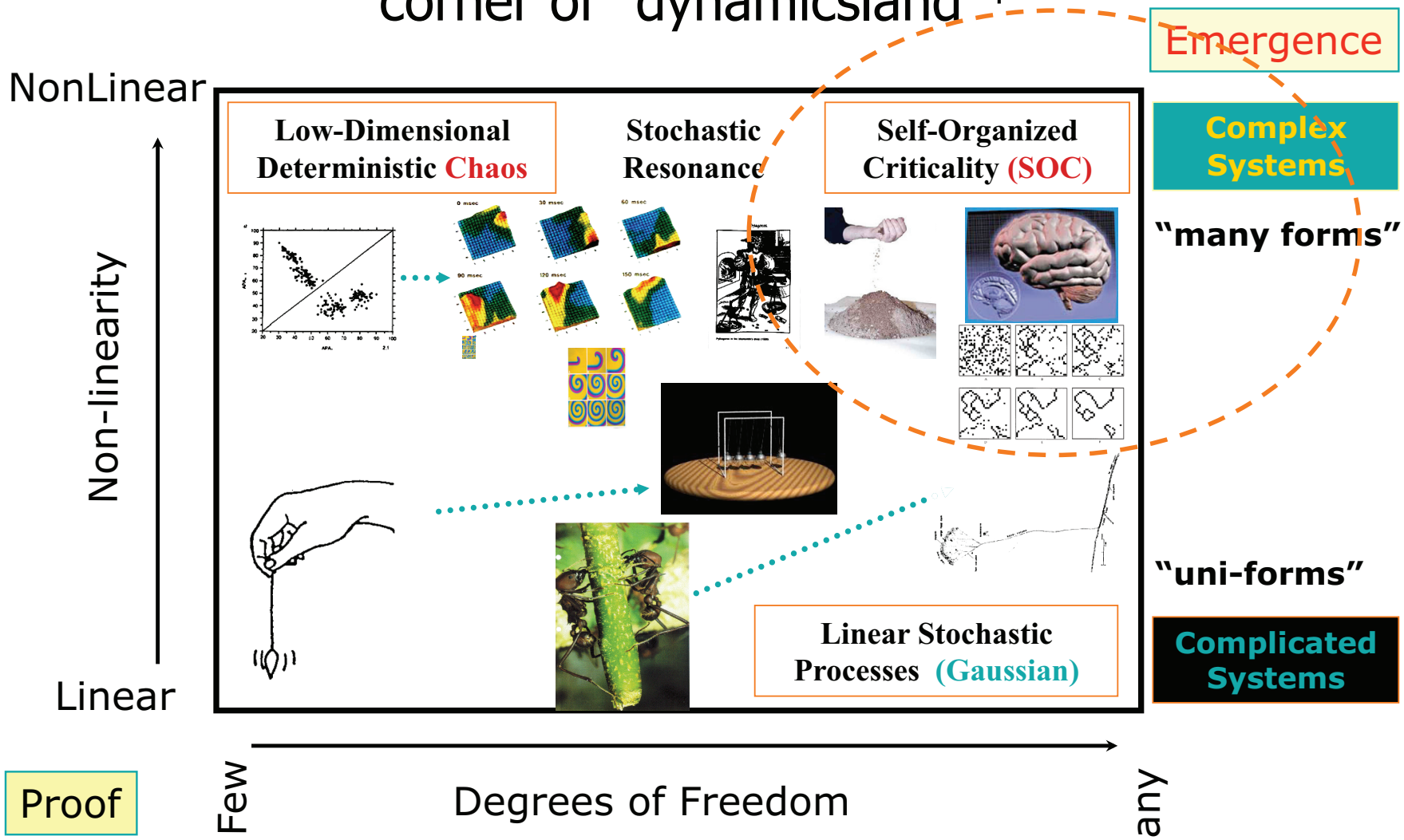
Question:

What mechanism produces

dynamical patterns that lack a characteristic scale

(thus so-called "scale-free")?

One Answer:
Scale-free dynamics is ubiquitous at the top-right corner of "dynamicsland"*

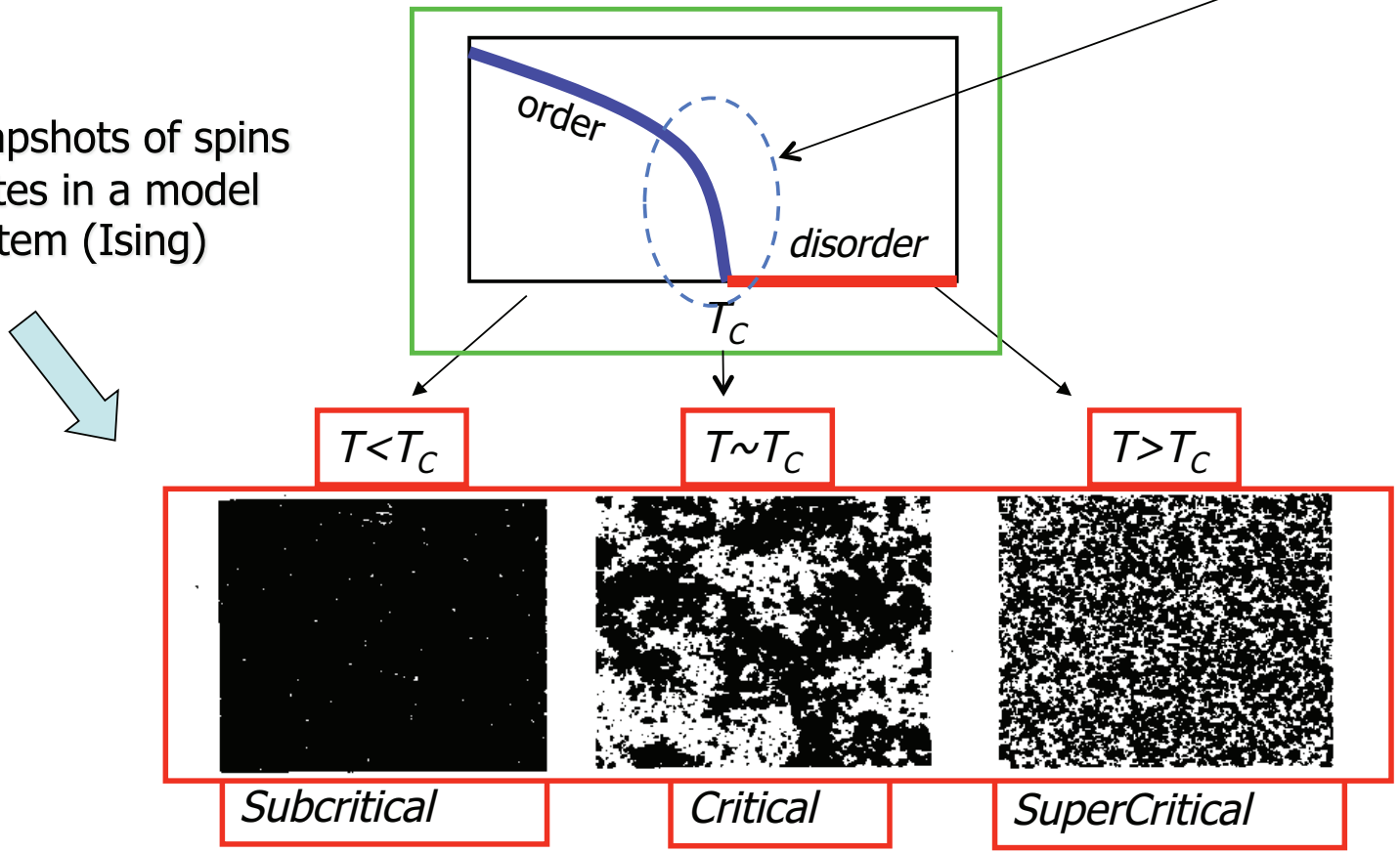


*Chialvo DR. Physica A, (2004)

One way to generate scale-free dynamic is being critical

Example: Ferromagnetic-paramagnetic Phase-Transition

Snapshots of spins states in a model system (Ising)



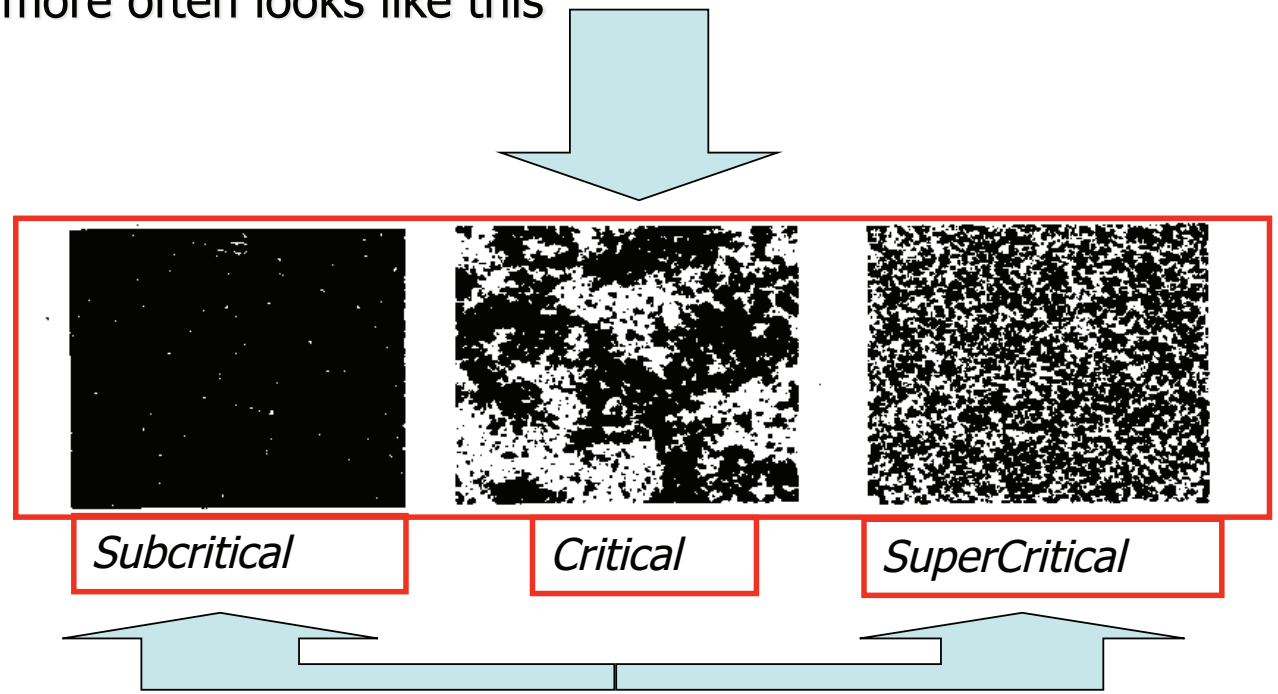
Snapshots of spins states in the Ising model.

Long range correlations emerges only at the phase transition

Which is related to the question:

Why do we need a brain at all?

Because the world around us - in which brains have to survive- more often looks like this



Never like that!

Why do we need a brain at all?

•In a sub-critical world everything would be simple and uniform - there would be nothing to learn.

•In a supercritical world, everything would be changing all the time - it would be impossible to learn.

The brain is only necessary to navigate in a complex, critical world .

Ok, even if the physical world is plenty of critical stuff but... Why the brain itself has too be Critical?

A brain not only have to remember, but also to forget and adapt.

•In a sub-critical brain memories would be frozen.

•In a supercritical brain, patterns change all the time so no long term memory would be possible.

To be highly susceptible, the brain itself has to be in the (in-between) critical state.

The critical brain conjecture

The brain is critical (and the world at large is also critical)

Fast cortical-subcortical "reconfigurations" needed to produce flexible adaptive behaviour can only be possible if the brain operates near a second order phase transition (i.e., critical).

If we are right and the brain is critical: What one should be able to observe?

I) At large scale[1]:
- Cortical Long range correlations in space and time (scale-free),
- divergence of correlation length.
- anti-correlated resting state networks, (i.e., ”zero magnetization”)

II) At smaller scale[2]:
- “Neuronal avalanches” is the normal homeostatic state of neocortical circuits. (“cortical-quakes”).

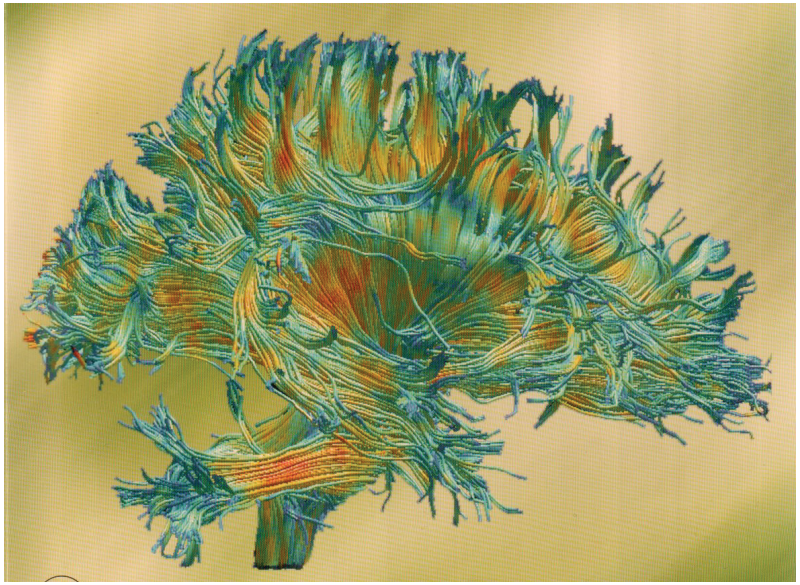
III) At behavioral level[3]:
- Adaptive behavior as “bursty” and apparently unstable, (always at the “edge of failing”, “rising the bar effect”)

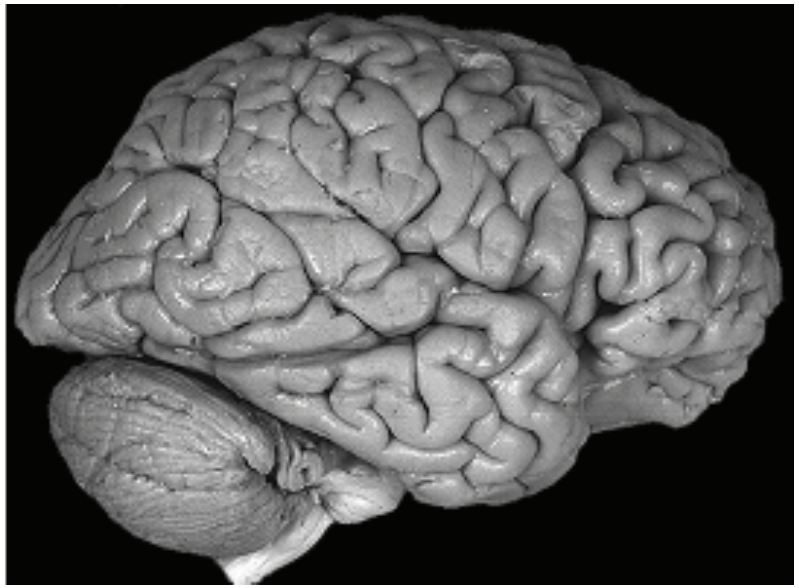
[1] Chialvo DR. Physica A, (2004); Eguiluz et al., Phys. Rev. Letters (2005); Chialvo (2005, 2006); Chialvo et al (2008); Fraiman et al., (2008), Baliki et al., J. Neuroscience (2008);

[2] Beggs & Plenz, J. Neuroscience (2003). Plenz & Chialvo, arxiv.org/abs/0912.5369, submitted 2010)

[3] Anteneodo & Chialvo, Chaos (2009).

I): Critical at Large Scale



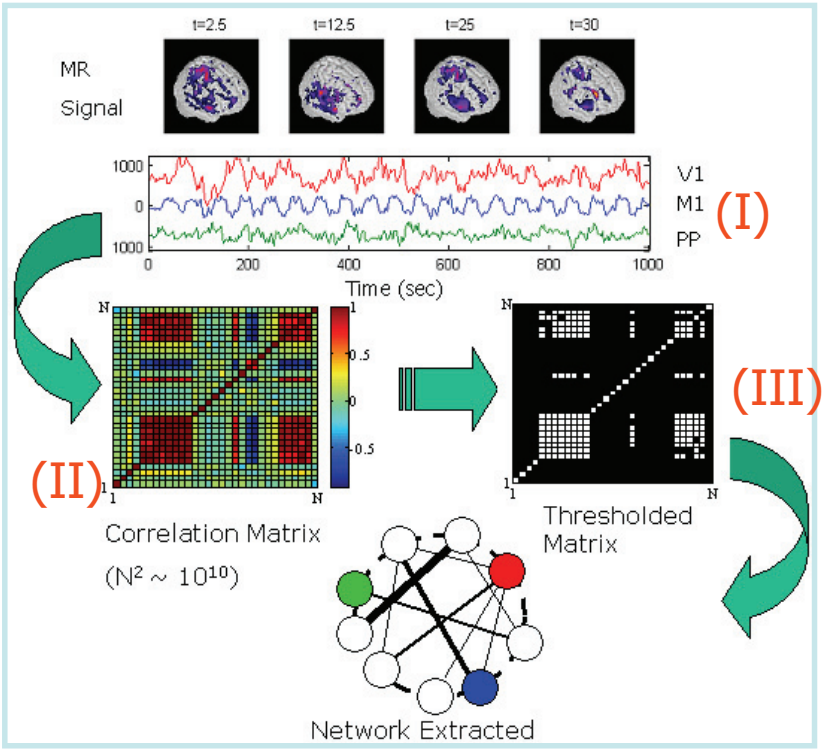


Cortical Long range correlations in space and time

fMRI

How to extract functional brain networks?

fMRI



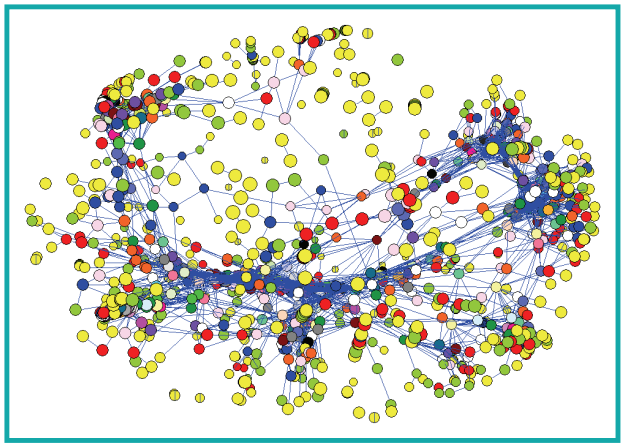
$$r(x_1,x_2) = \frac{\langle V(x_1,t) \quad V(x_2,t)\rangle - \langle V(x_1,t)\rangle\langle V(x_2,t)\rangle}{\sigma(V(x_1))\,\sigma(V(x_2))}$$

$$\sigma^2(V(x)) = \langle V(x,t)^2 \rangle - \langle V(x,t) \rangle^2$$

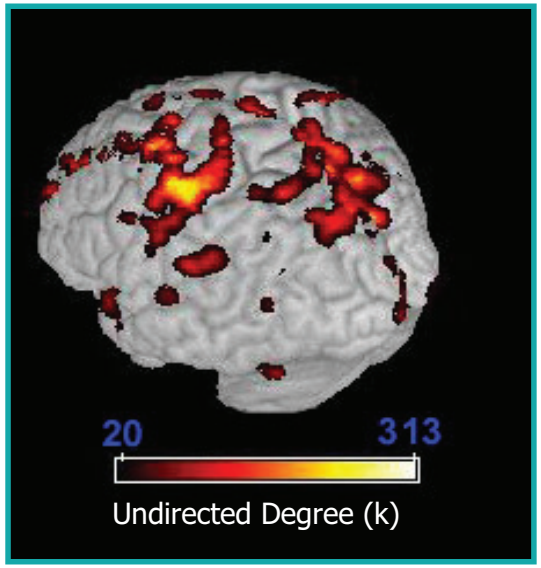
From Eguiluz et al, Phys. Rev. Letters (2005).

My brain's network

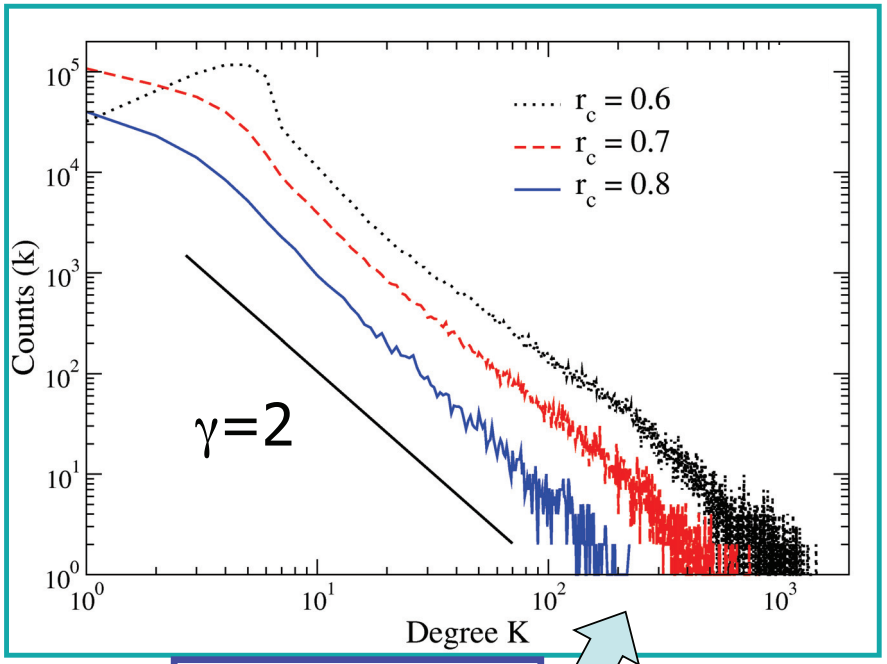
Topology



Topography



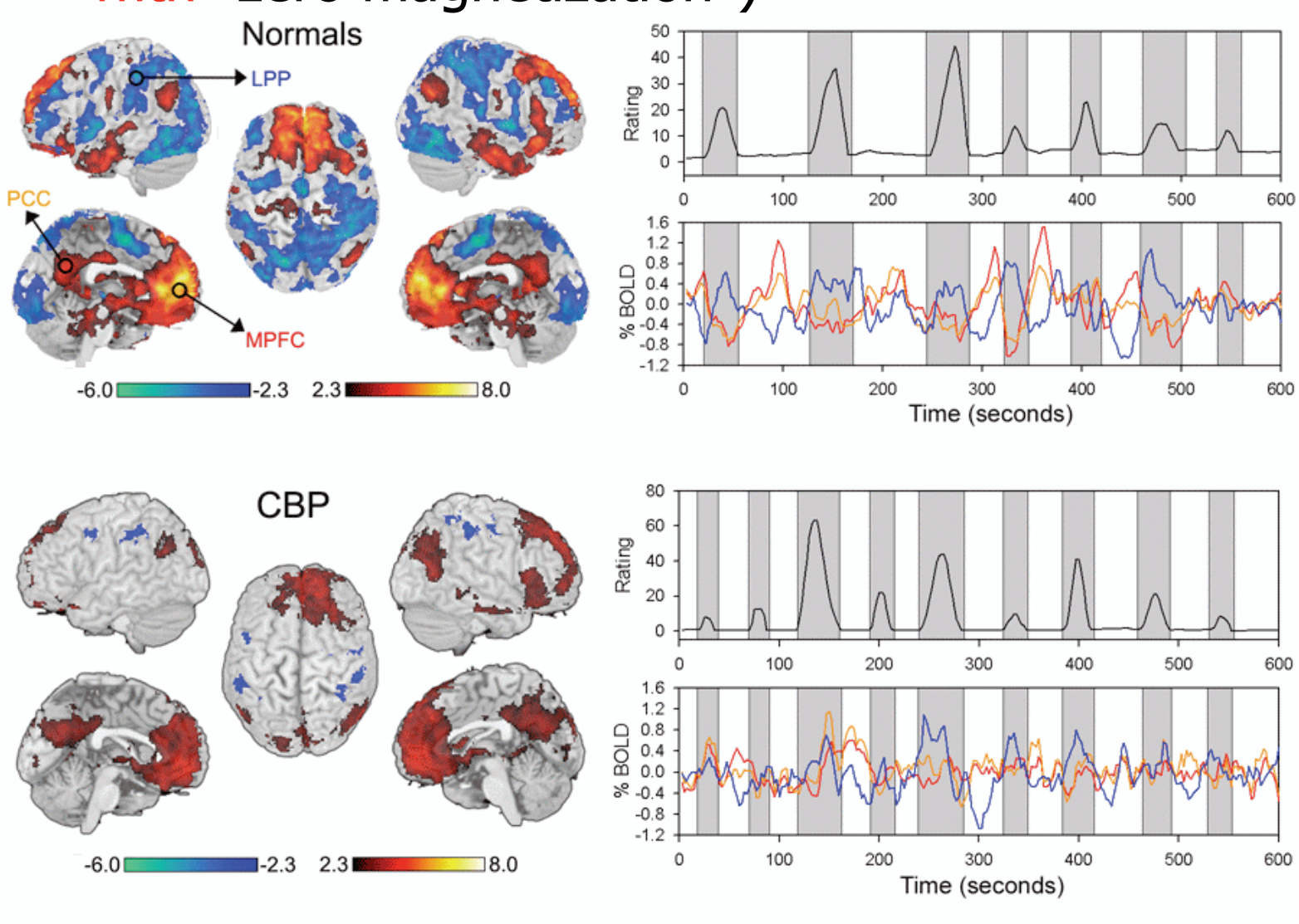
Scale free distribution of functional connections



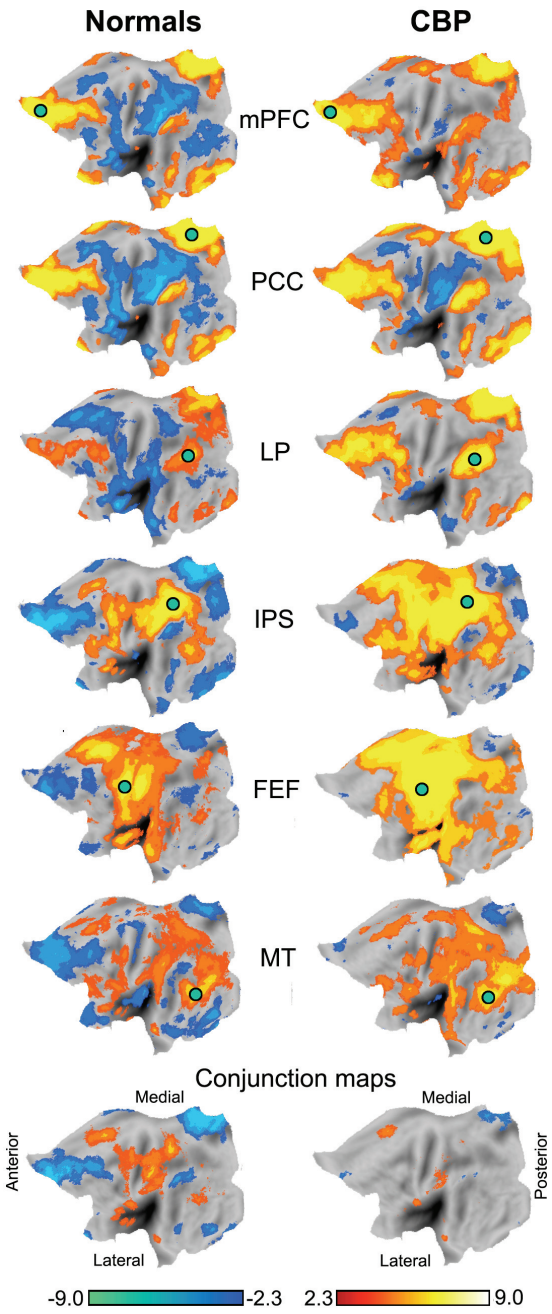
Few but very well connected brain sites

From Eguiluz et al, Phys. Rev. Letters (2005).

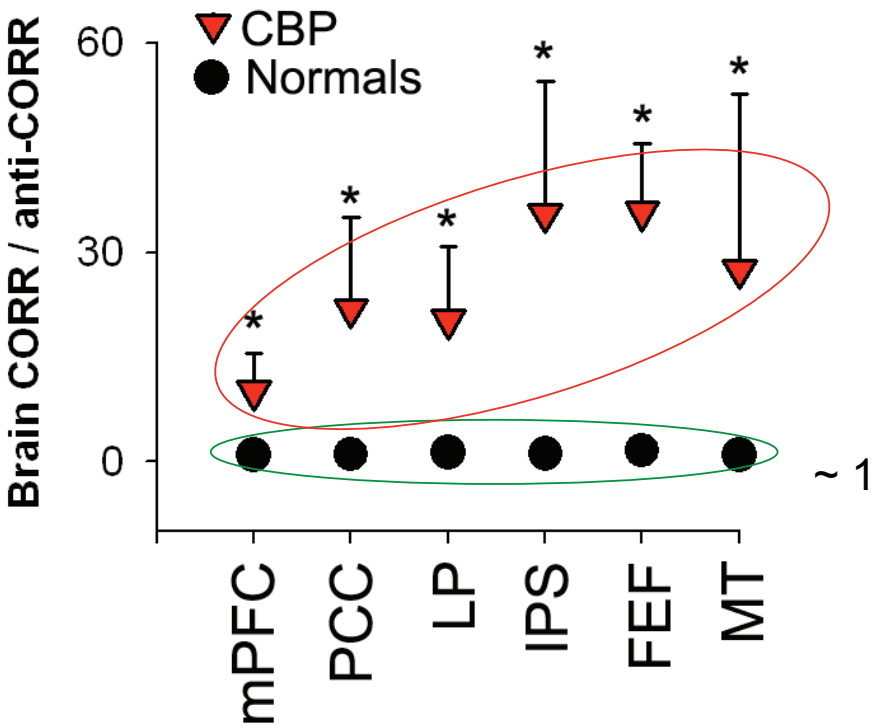
Anti-correlated domains (i.e., long range correlations with "zero magnetization")



Baliki et al. 2008, "Beyond feeling: chronic pain hurts the brain disrupting the default-mode network dynamics"



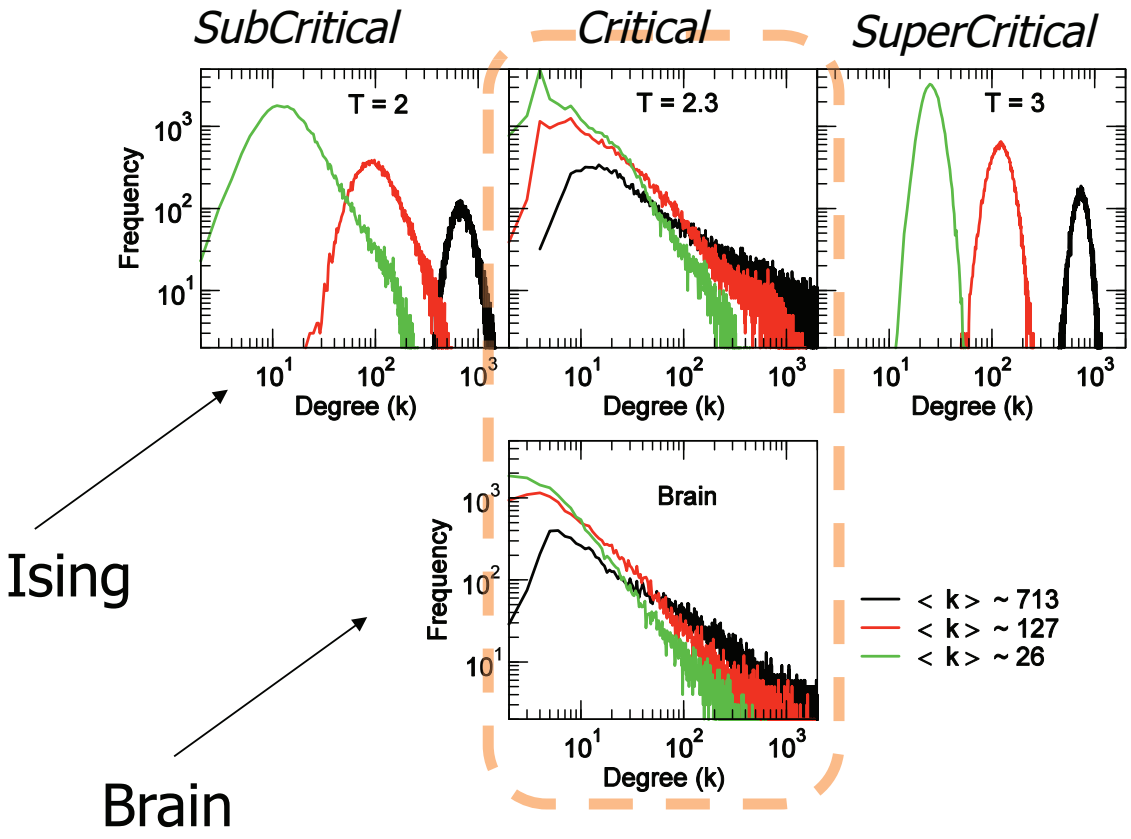
Note the huge decrease in the brain deactivations (blue) in CBP patients



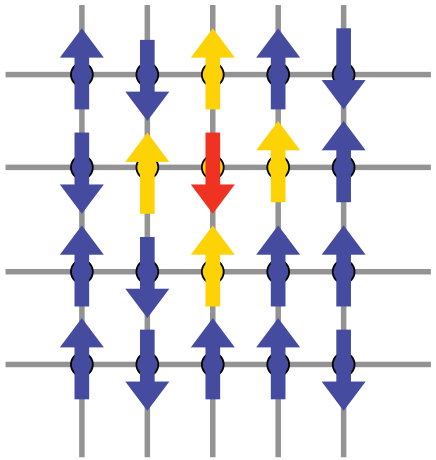
The bottom line:
Chronic pain patients show a disrupted activation/deactivation balance.

From Baliki et al, J. Neuroscience (2008).

Critical Ising networks mimic brain networks



Positive correlated networks



Only local positive interactions

$$E=-J \sum_{<i,j>} S_i S_j - B \sum_k S_k$$

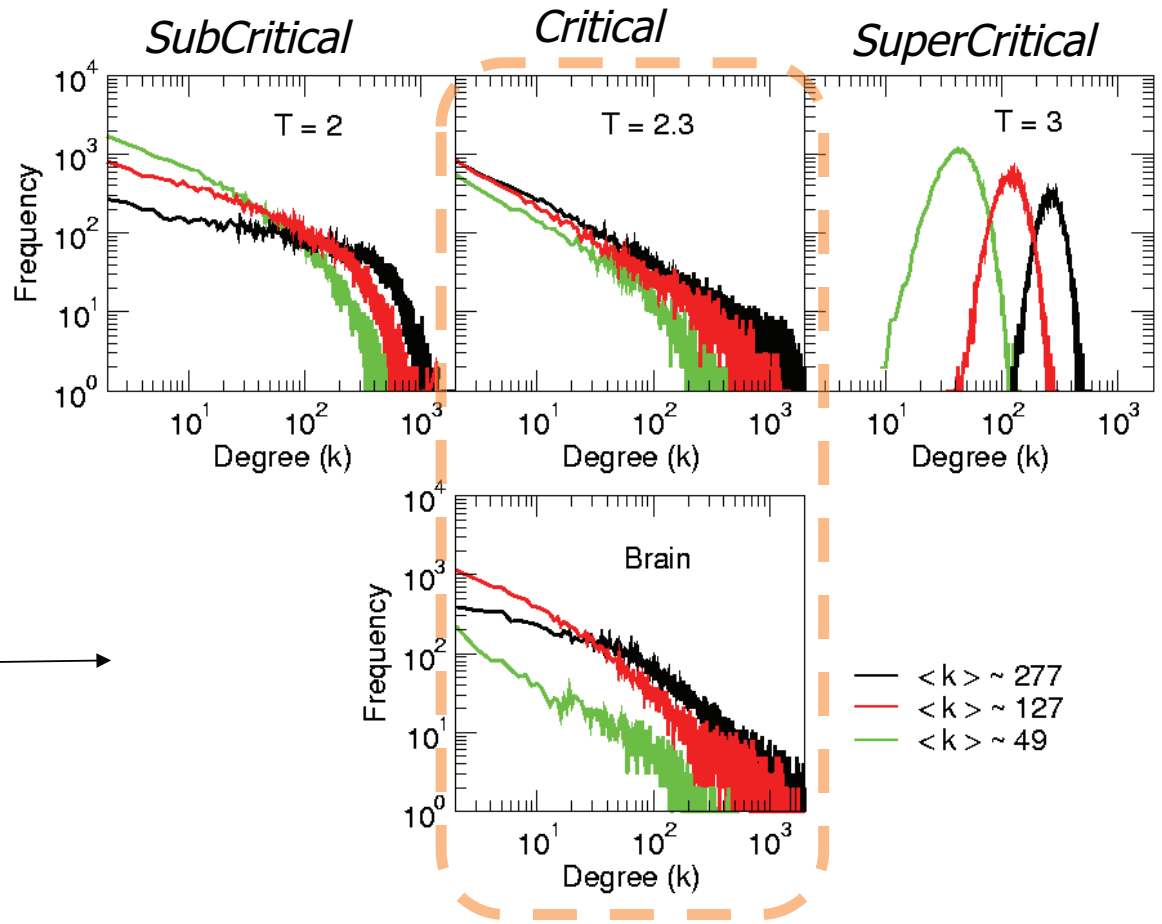
From Chialvo, Balenzuela & Fraiman. The brain: What is critical about it? (arXiv.org/ cond-mat/0804.0032); Fraiman, Balenzuela, Foss & Chialvo, Ising like dynamics in large-scale brain networks. (arXiv.org/ cond-mat/0811.3721), Phys Rev. E. (2008).

Critical Ising networks mimic brain networks

Negative correlated networks

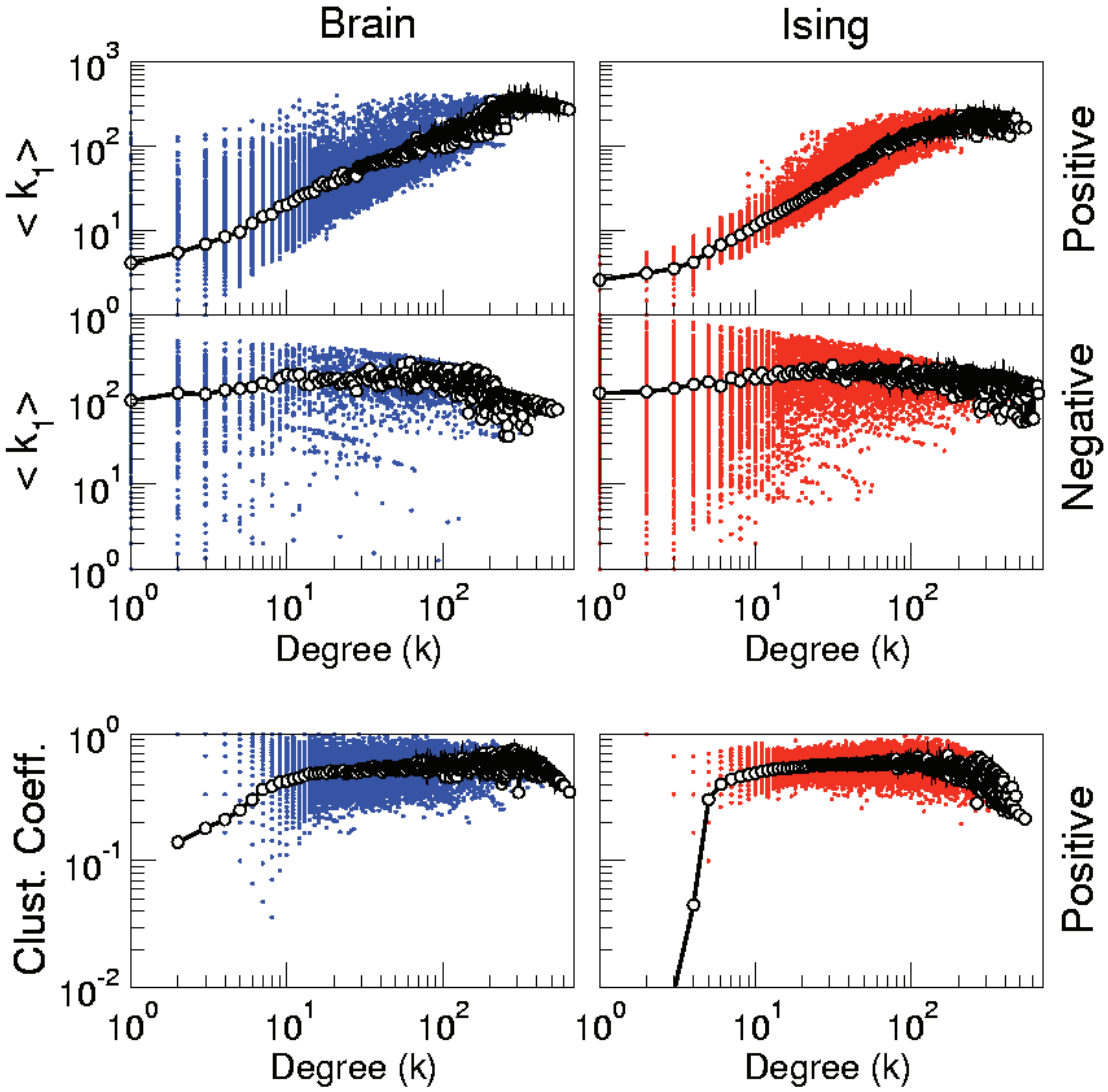
Ising →

Brain →



Negative correlations with fat tails similar to the brain data appear in the Ising data, despite the absence of negative "structural" interactions (i.e. no "inhibitory" connectivity).

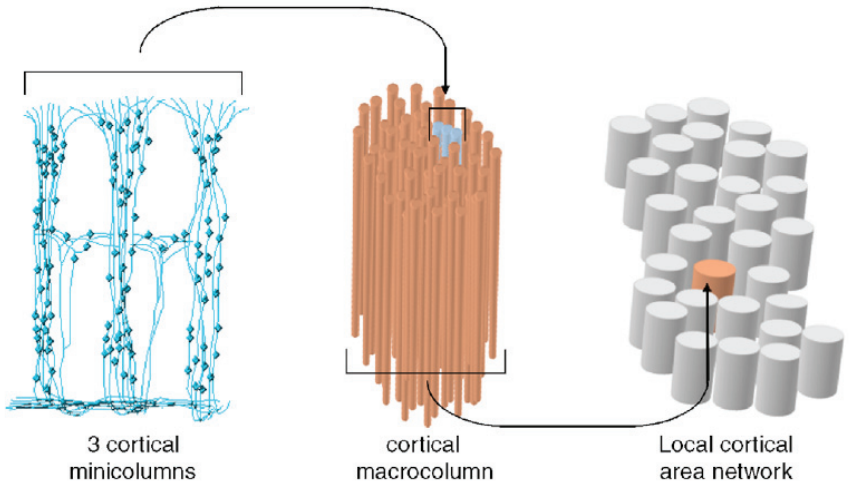
Assortativity



From Fraiman, Balenzuela, Foss & Chialvo, Ising like dynamics in large-scale brain networks. (arXiv.org/ cond-mat/0811.3721), Phys Rev. E. (2008).

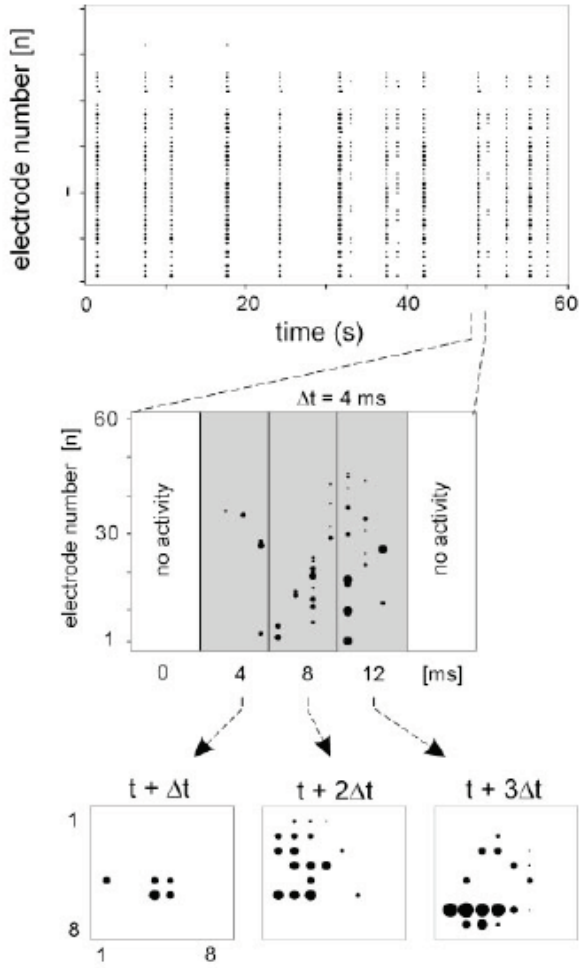
II): Critical at Small scale

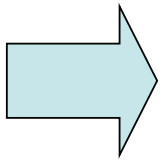
•Neuronal avalanches are peculiar dynamics occurring in the cortex (probably like an "action potential traveling trough cortex*"...)

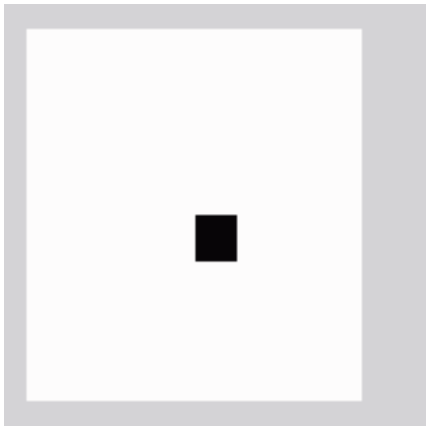


*But not a traveling wave

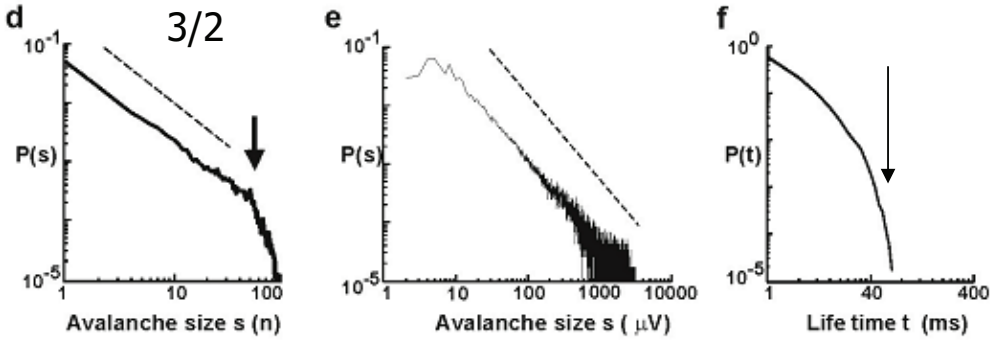
What is an avalanche (here from cultured rat cerebral cortex)





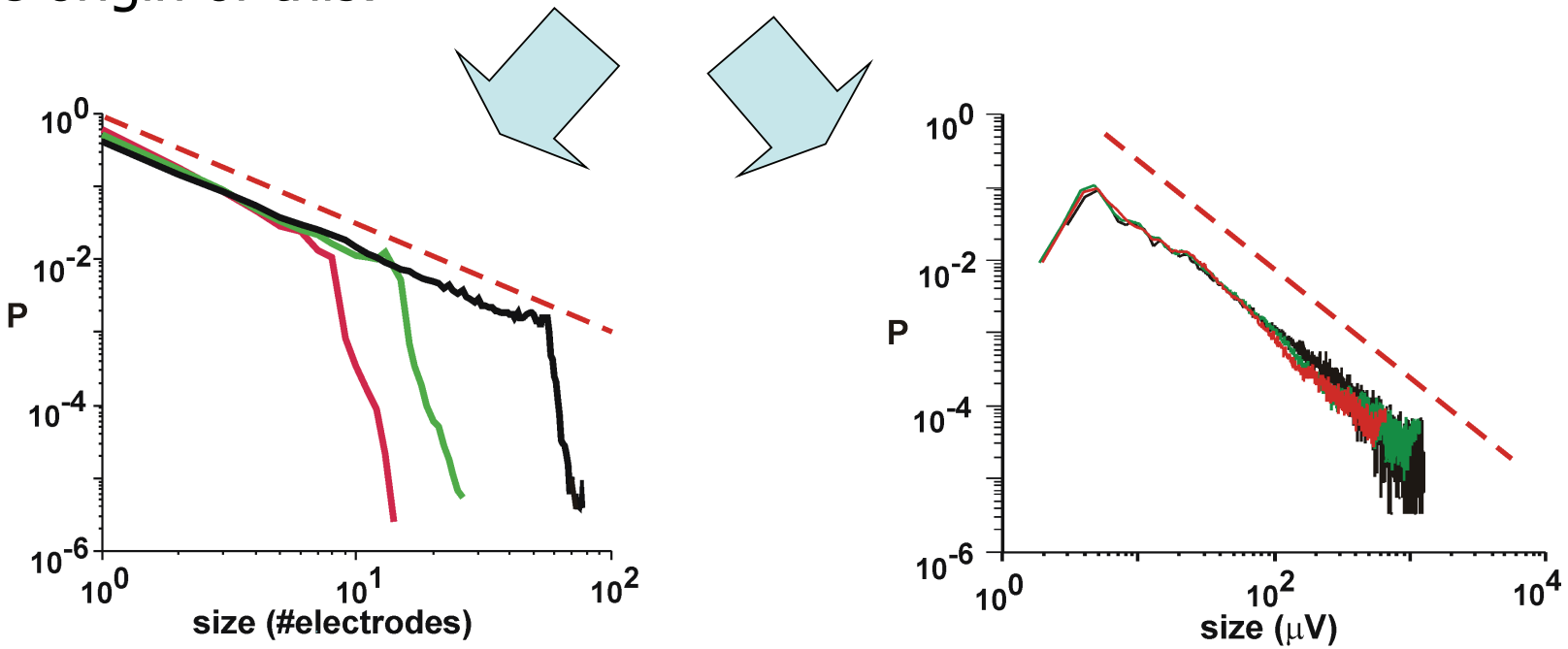


Longest ~ 0.1 sec)



Beggs J. & Plenz D, Neuronal Avalanches in Neocortical Circuits J. of Neuroscience, 3 23 (2003).

All Models of neuronal avalanches foccus on explaining (or not) the origin of this:



avalanche sizes distribution

What spatiotemporal properties of cortical avalanches are rigourously related to CRITICAL dynamics.

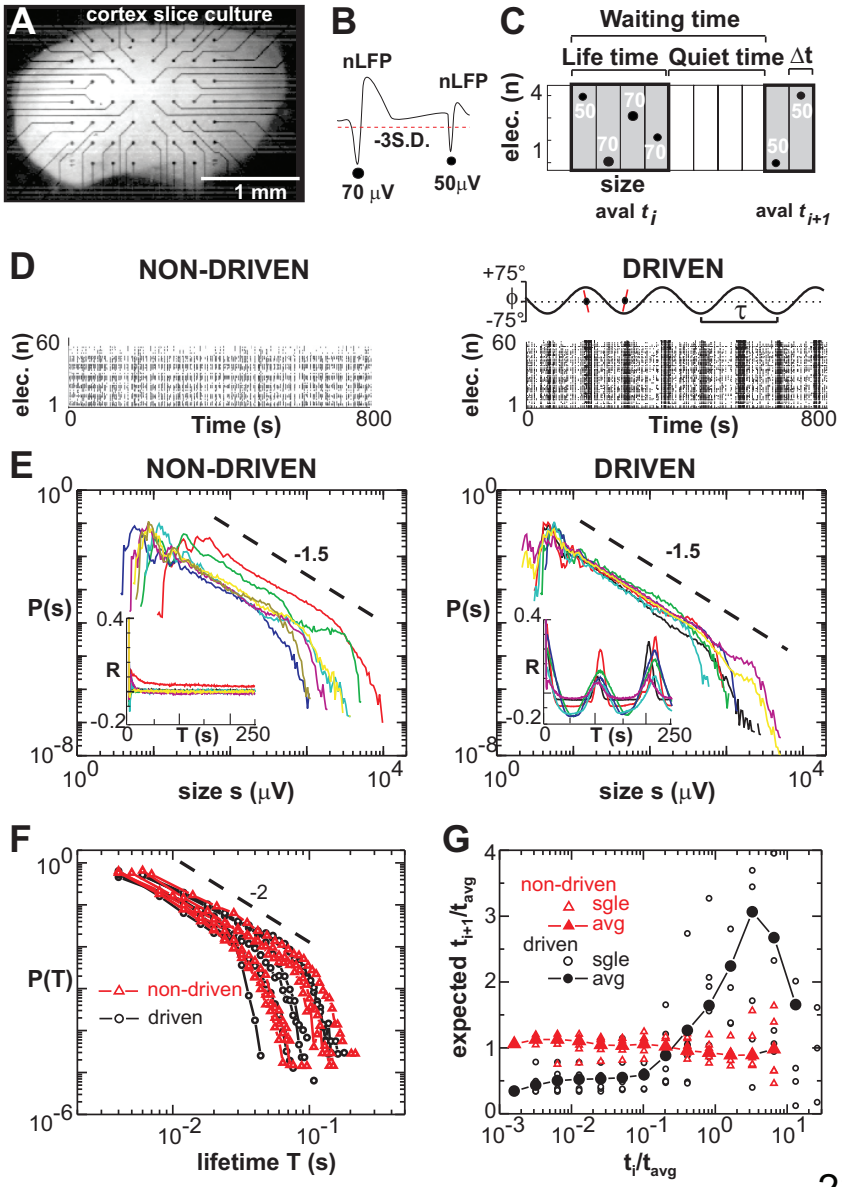
Is there a separation of time scales and if so how long lasts?

For that we look at spontaneous as well as slowly driven cortical cultures

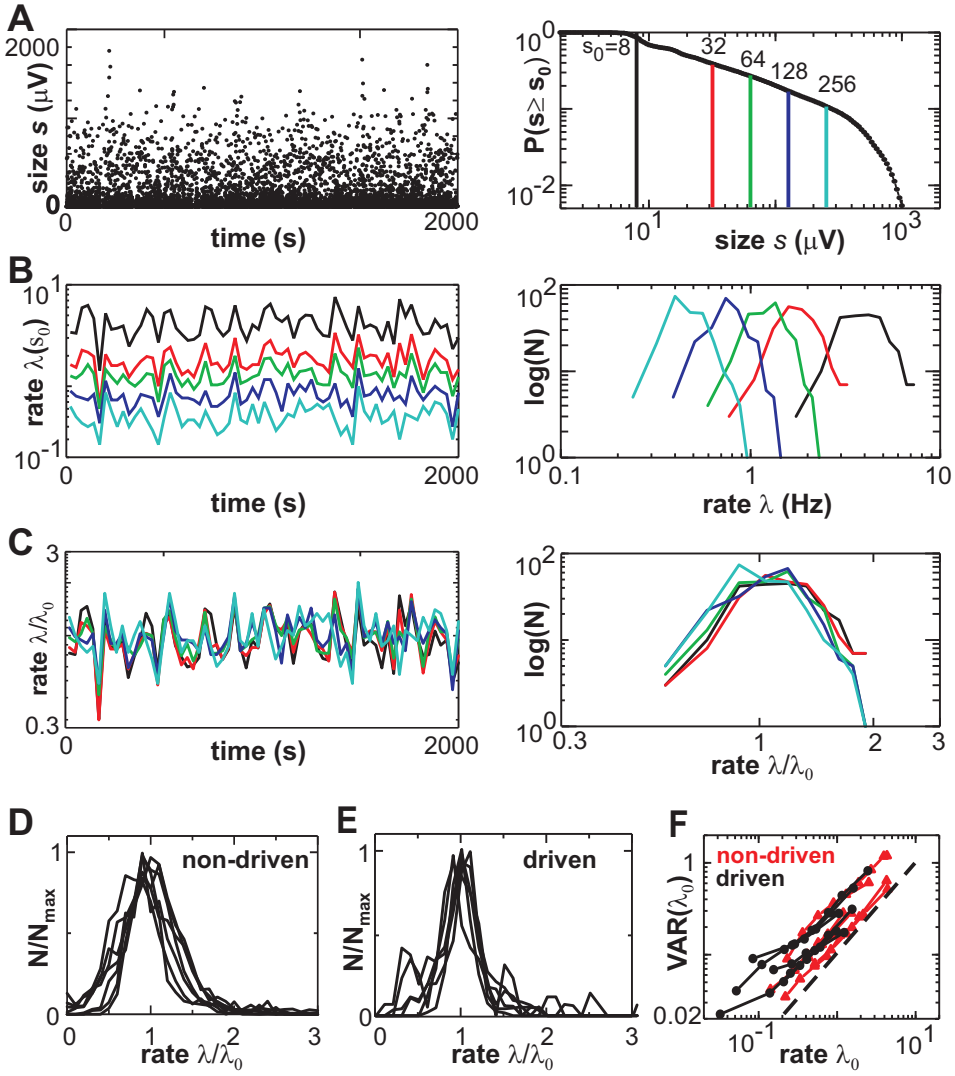
Separation of time scales:

the (fast) time scale of the avalanches is not perturbed by the (slow) drive.

From Plenz & Chialvo, arxiv.org/abs/0912.5369, submitted 2010)



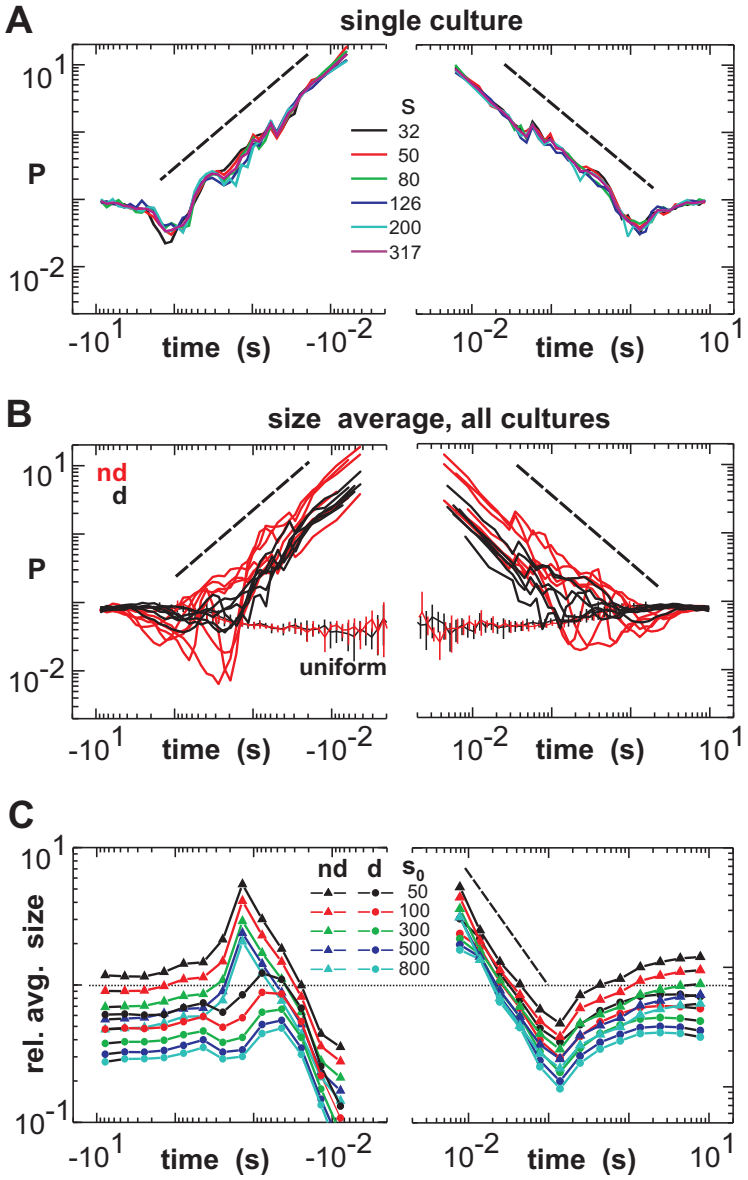
Is the avalanche size distribution stationary? Yes



These results definitely exclude claims arguing about a trivial stochastic origin for the power law avalanche size distribution.

From Plenz & Chialvo, arxiv.org/abs/0912.5369, submitted 2010)

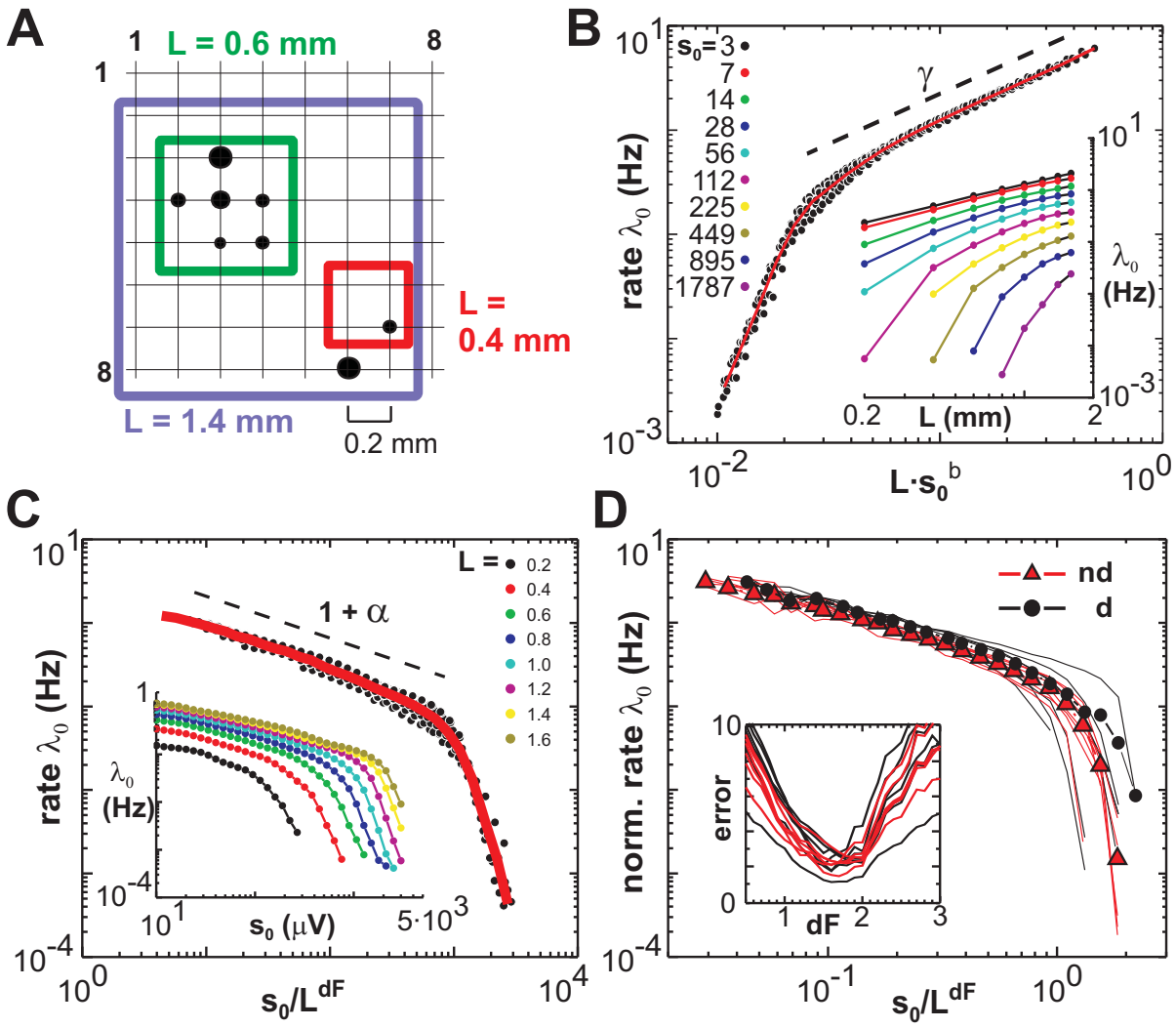
Omori Law: Number of avalanches as a function of time from a given avalanche



From Plenz & Chialvo, arxiv.org/abs/0912.5369, submitted 2010)

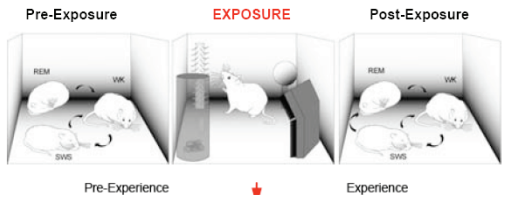
Avalanche' rate scaling with space

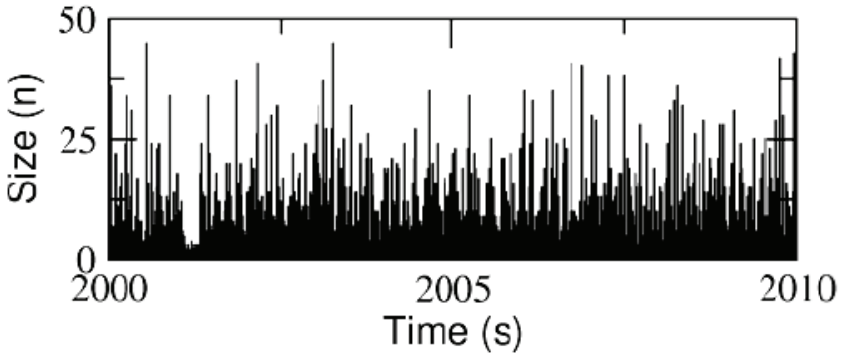
Avalanches spread as a fractal

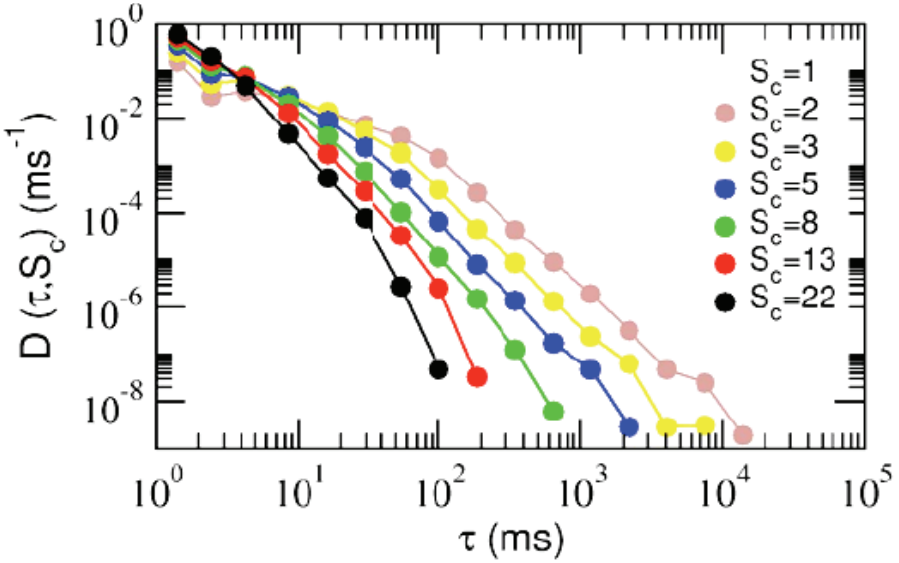


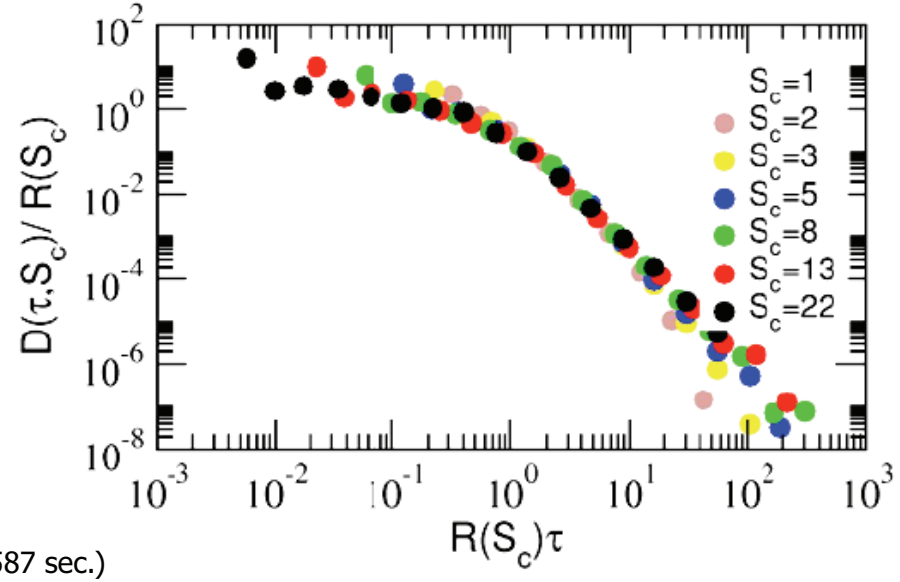
From Plenz & Chialvo, arxiv.org/abs/0912.5369, submitted 2010)

what about in vivo?







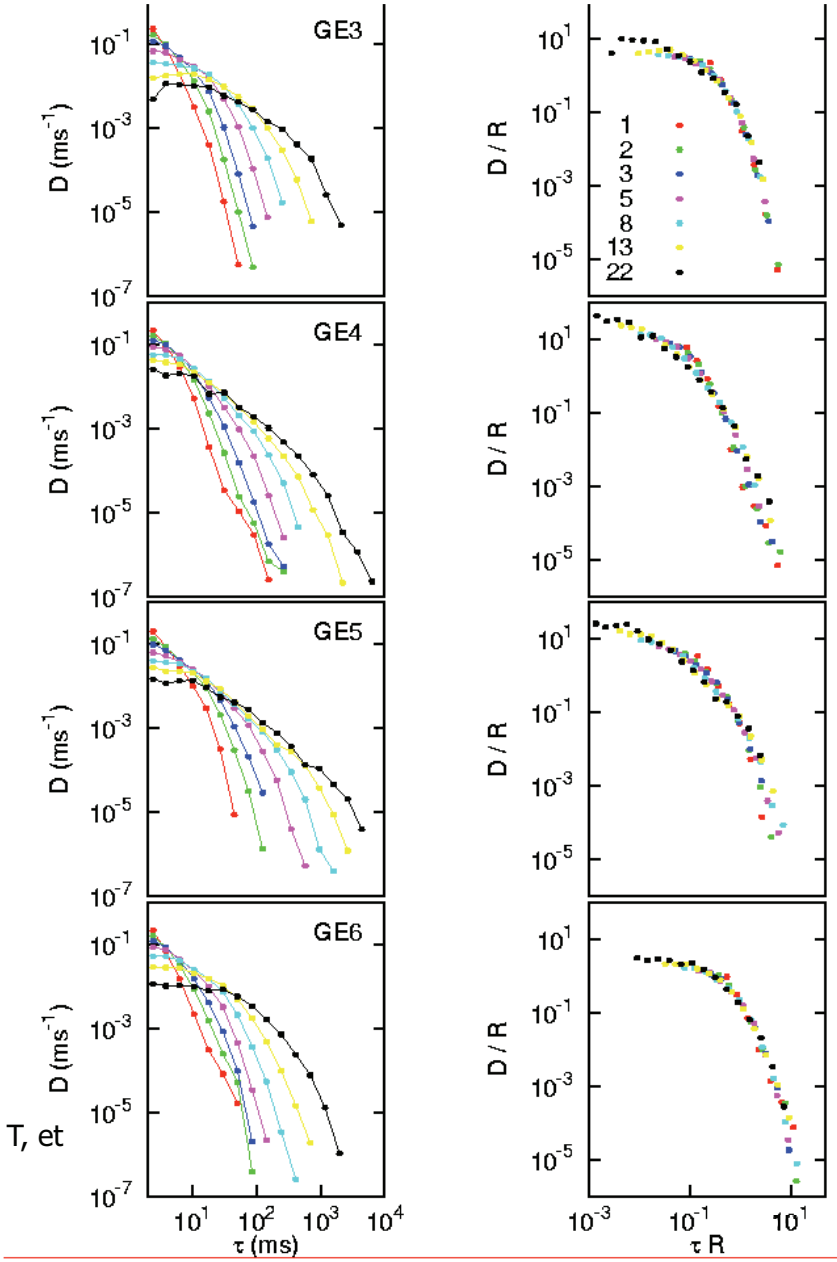


(415254 avalanches in SI cortex of a freely moving rat during 4587 sec.)

"Scaling in the Recurrence of Neuronal Avalanches in vivo", Ribeiro T, et al,unpublished 2009)

In vivo

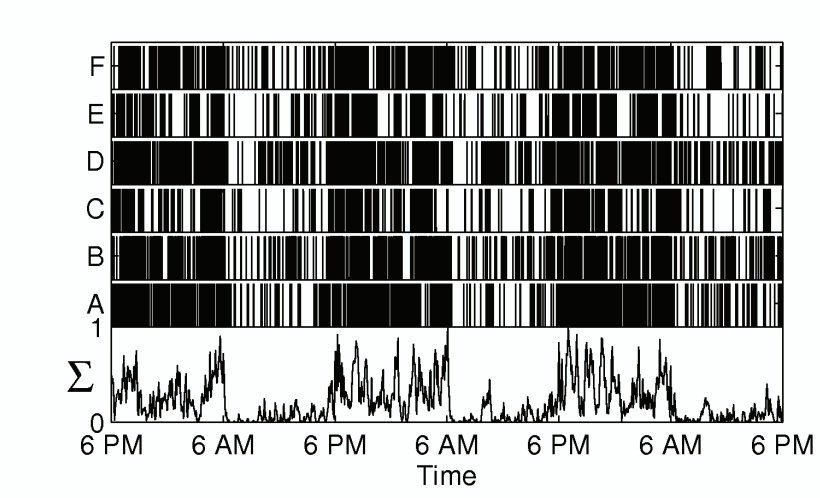
4 animals exhibiting the same scaling during awake state

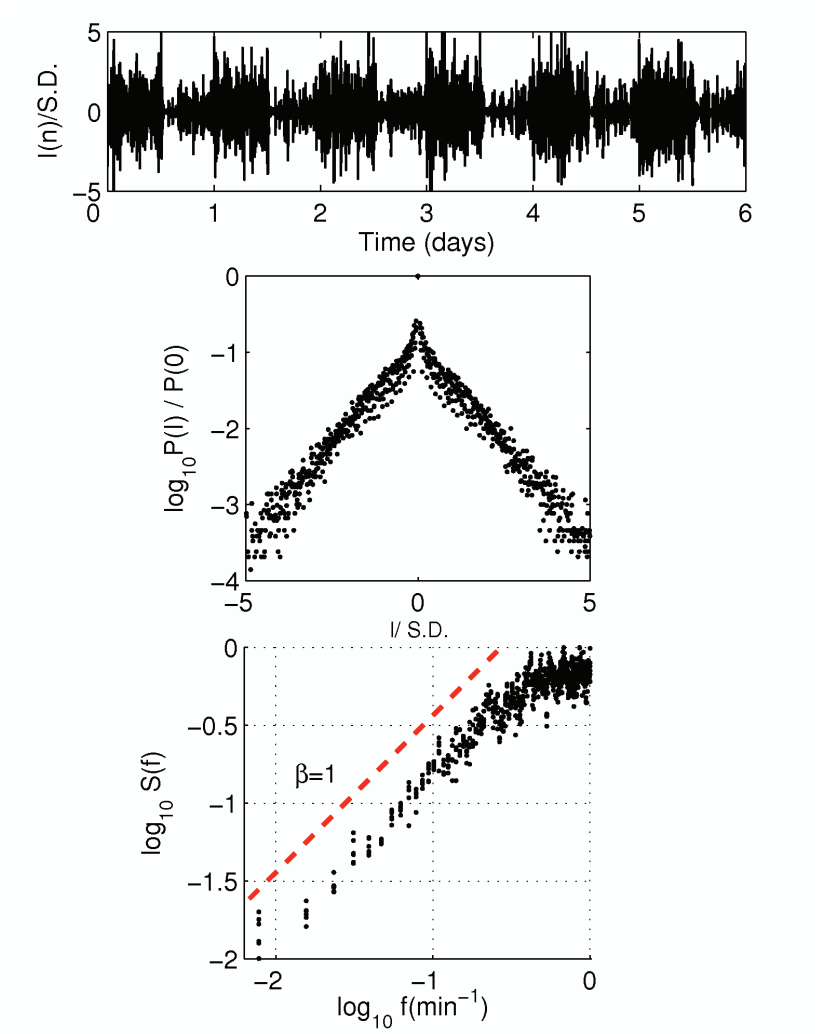


"Scaling in the Recurrence of Neuronal Avalanches in vivo", Ribeiro T, et al unpublished 2009)

III): Behavior

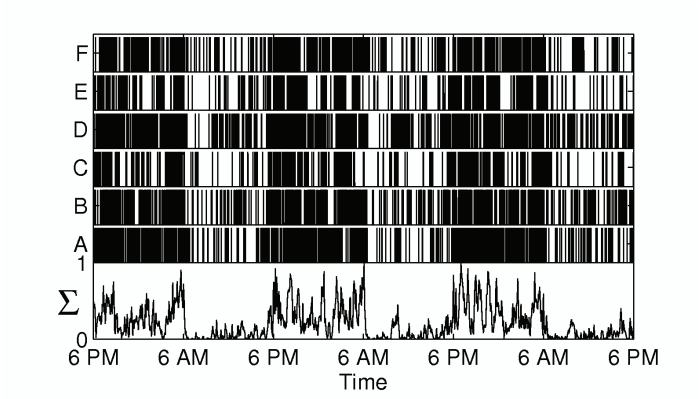
Behavior: is there an average rate for animal motion?

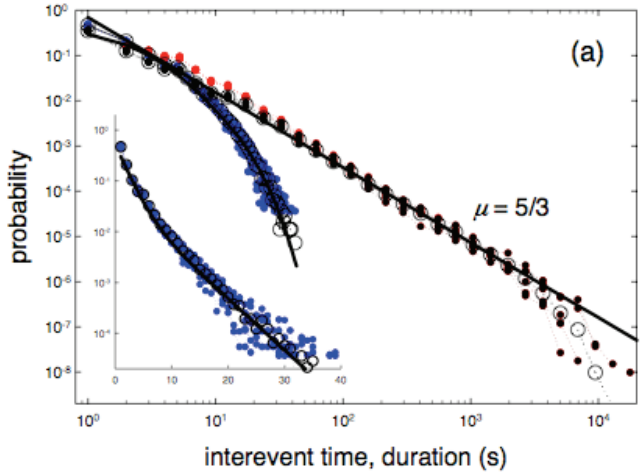


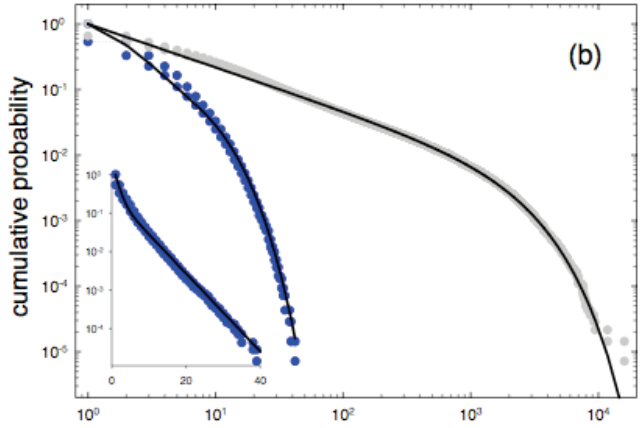


From Anteneodo and Chialvo, Chaos(2009)

Wish a scale free life? stop working hard, scaling is due to inactivity pauses!



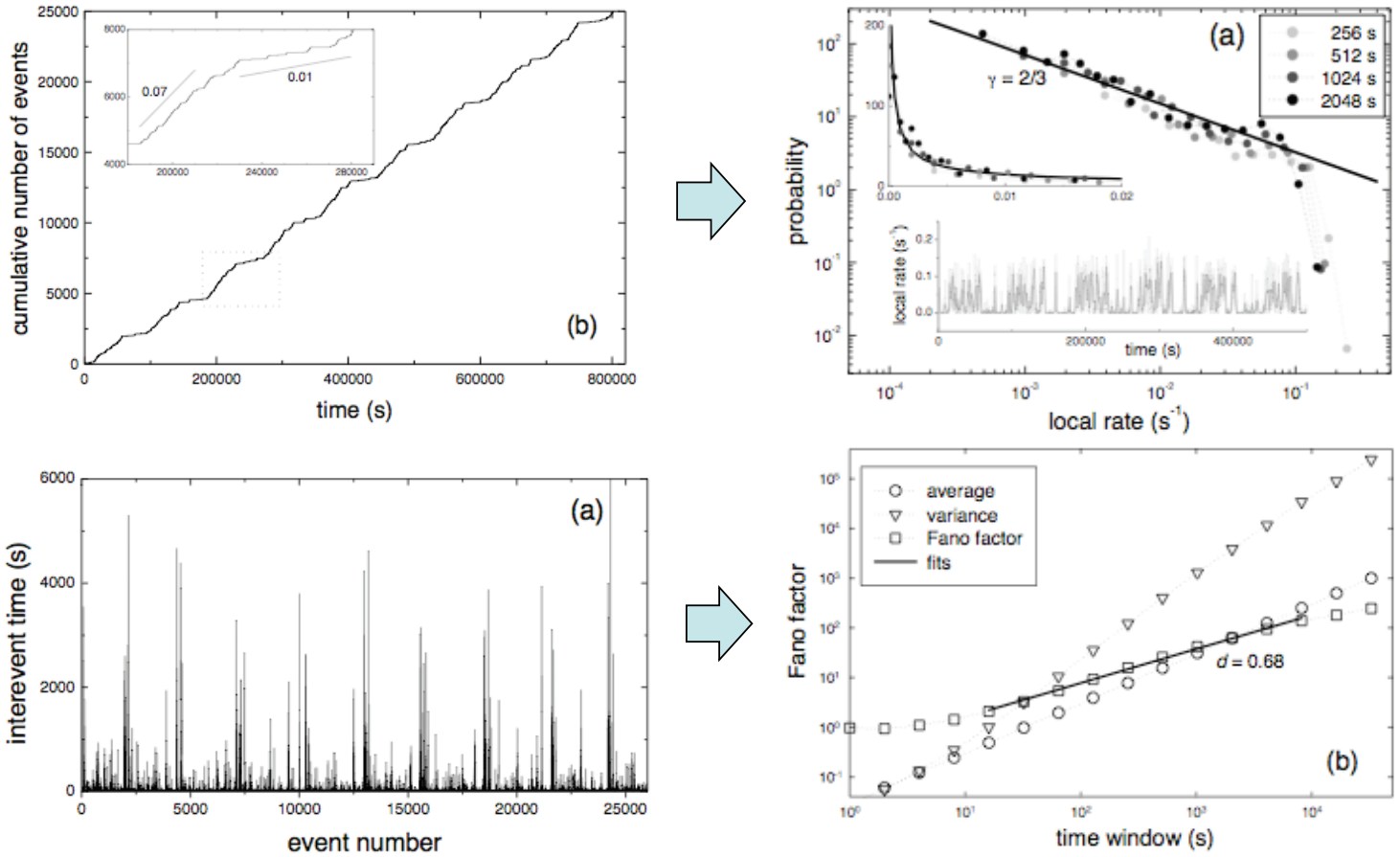




From Anteneodo and Chialvo, Chaos(2009)

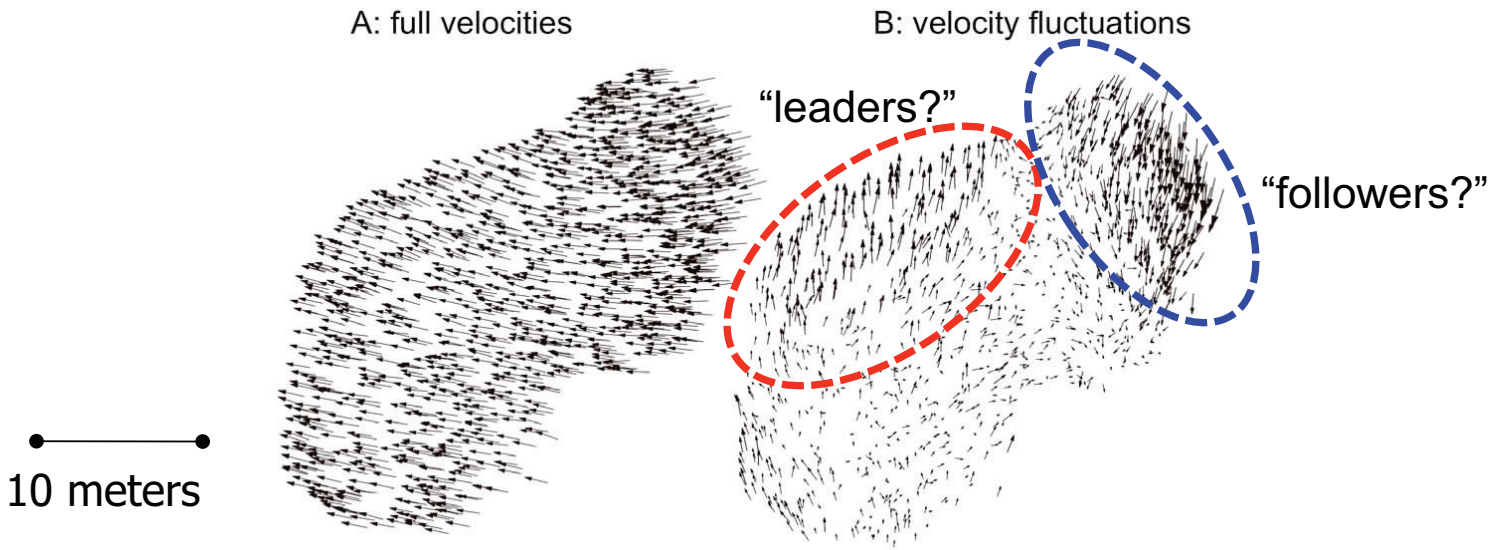
More on scaling and inactivity pauses

Inactivity pauses

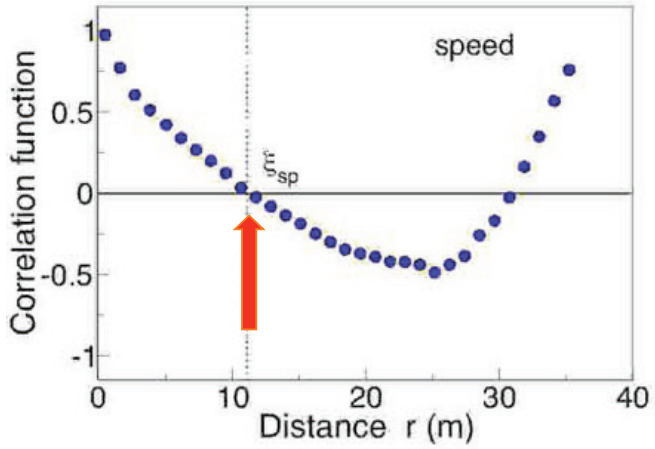


From Anteneodo and Chialvo, Chaos(2009)

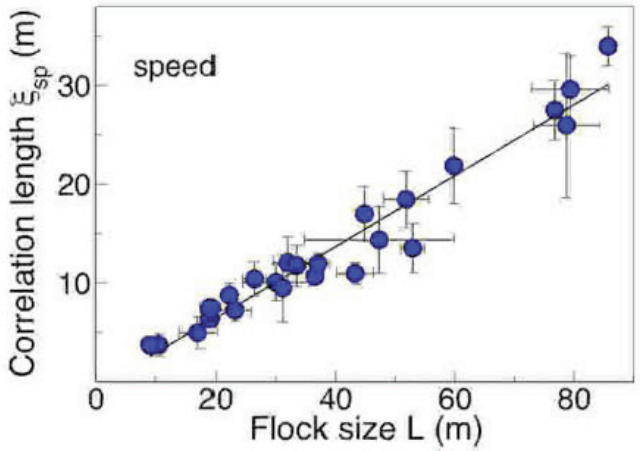
Back to collectivity



Correlation function of one flock



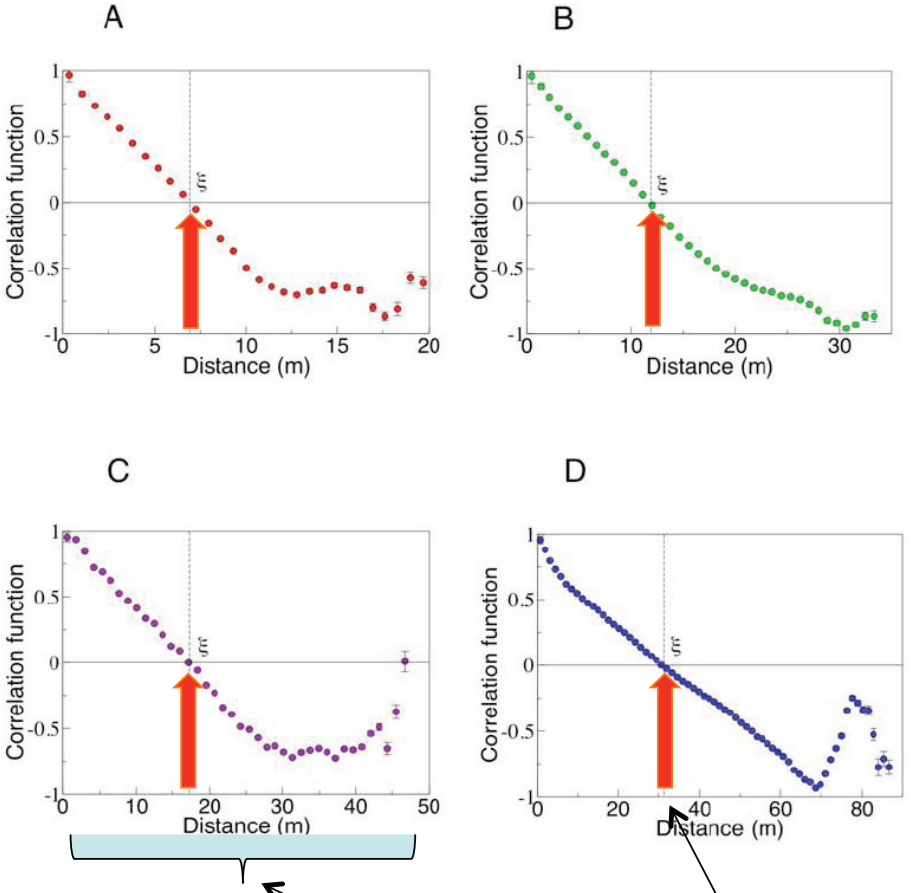
Correlation length of many flocks

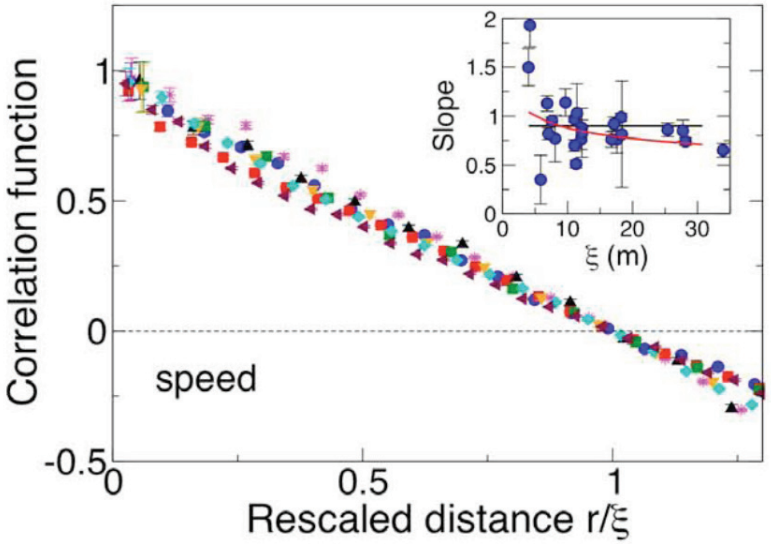


From Cavagna et al, Scale-free correlations in bird flocks, arXiv:0911.4393, (2010)

All flocks, big and small obeys the same laws*

In english: Two birds 1 meter apart, flying in a flock of 10 meters are equally correlated than two birds separated 10 meters on a flock of 100 meters…



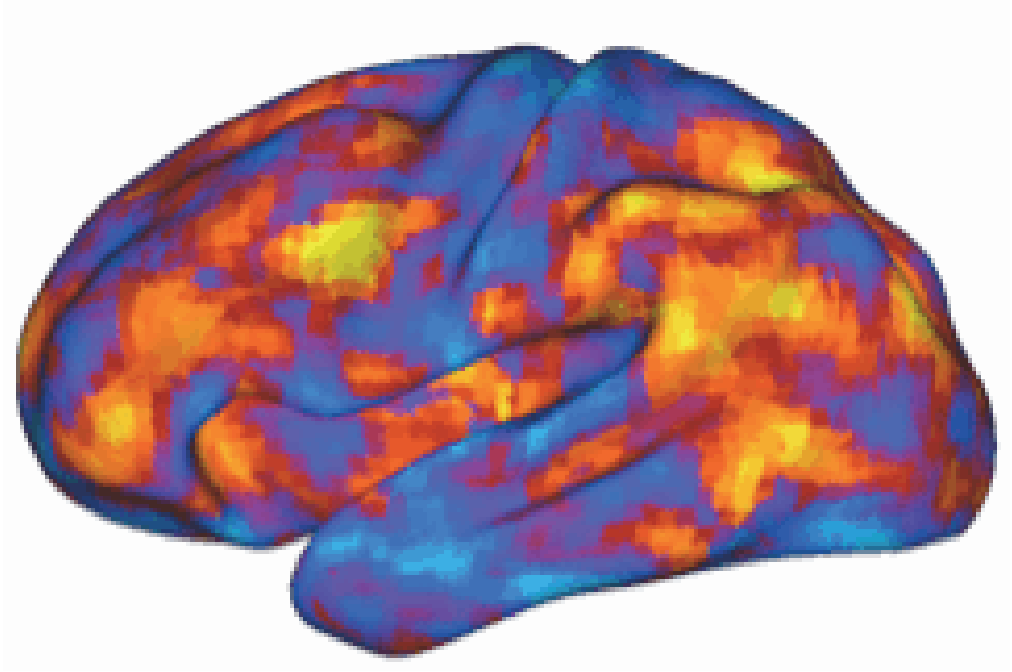


Rescaling the distance axis by its correlation length gives a unique correlation function

*From Cavagna et al, Scale-free correlations in bird flocks, arXiv:0911.4393, (2010)

*Let do the same for the brain at rest**

fMRI data from a healthy subject during resting state, shown about 13 times faster than real time.



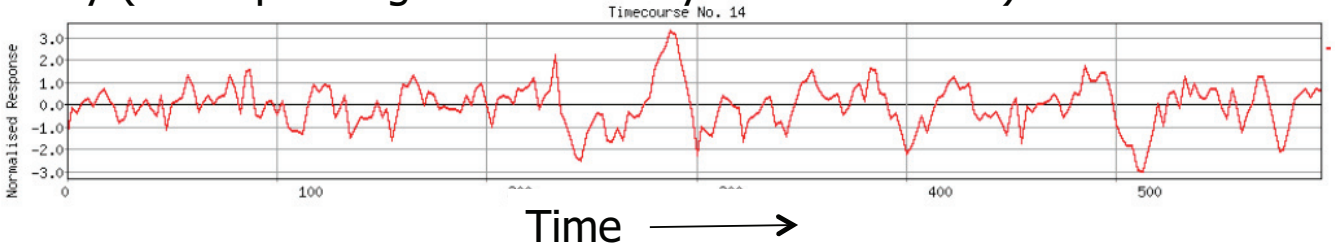
*From Chialvo & Fraiman unpublished 2009)

Resting state networks: Appropriate mathematical analysis of the temporal activity of brain fMRI BOLD signals **at rest** uncovers about **10 distinct interacting "networks"**.

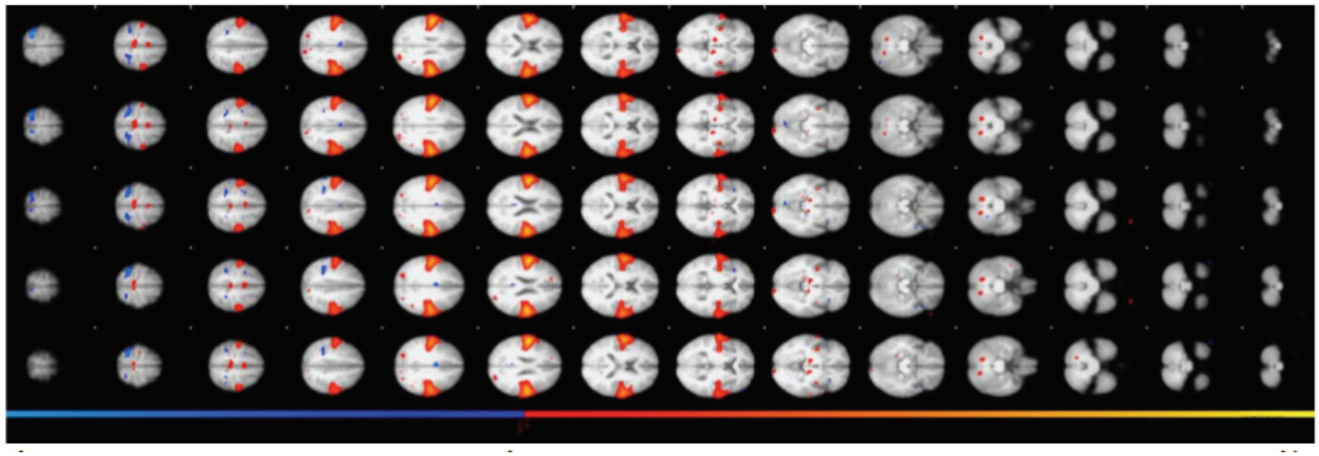
Think about the Resting State Networks as
•orchestras (networks)
•playing different symphonies (BOLD signals)
•at various parks (brain regions) of a city.

Here one symphony (corresponding to the sensory motor network):

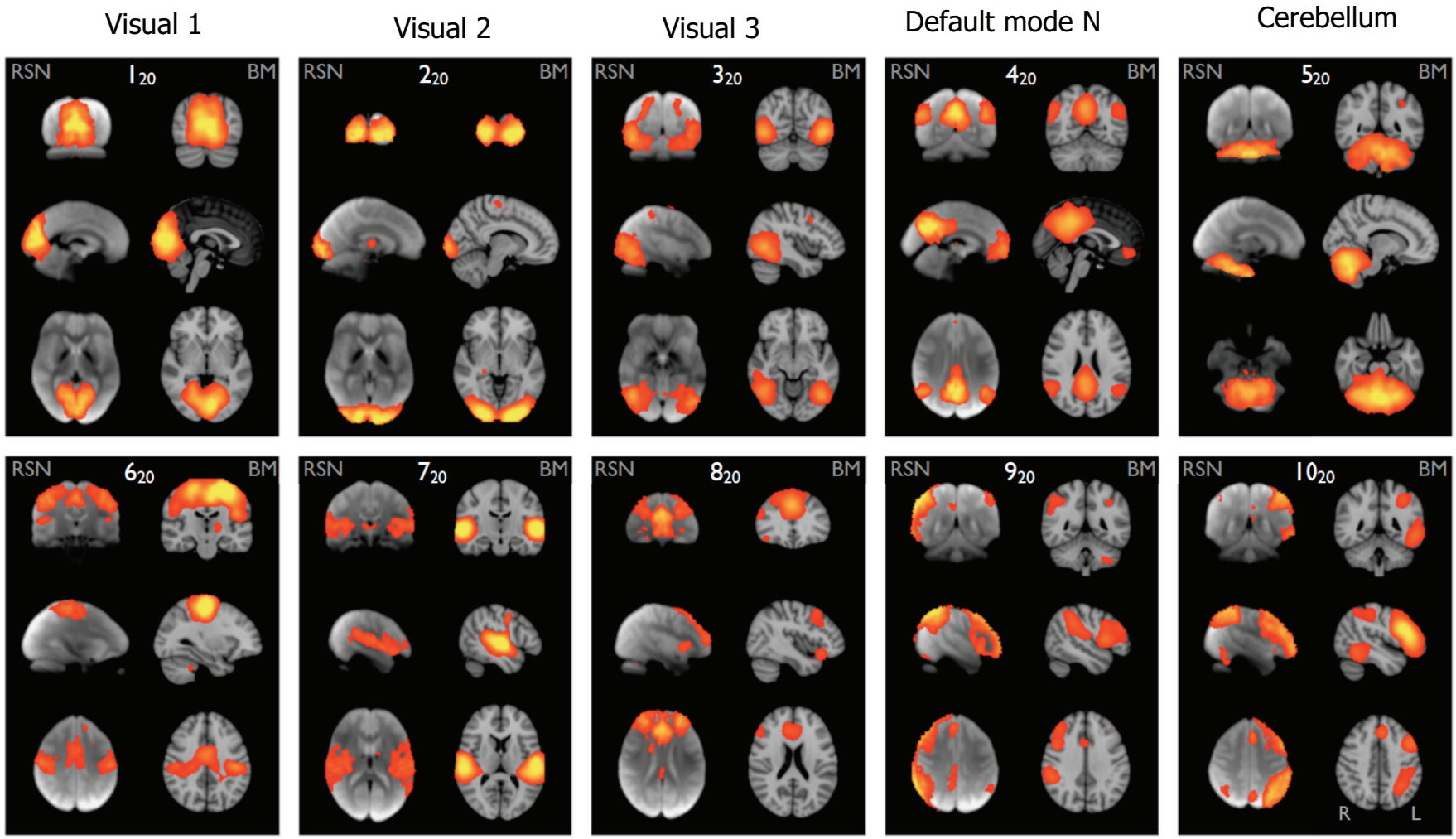
One piece of music



Four bands playing it

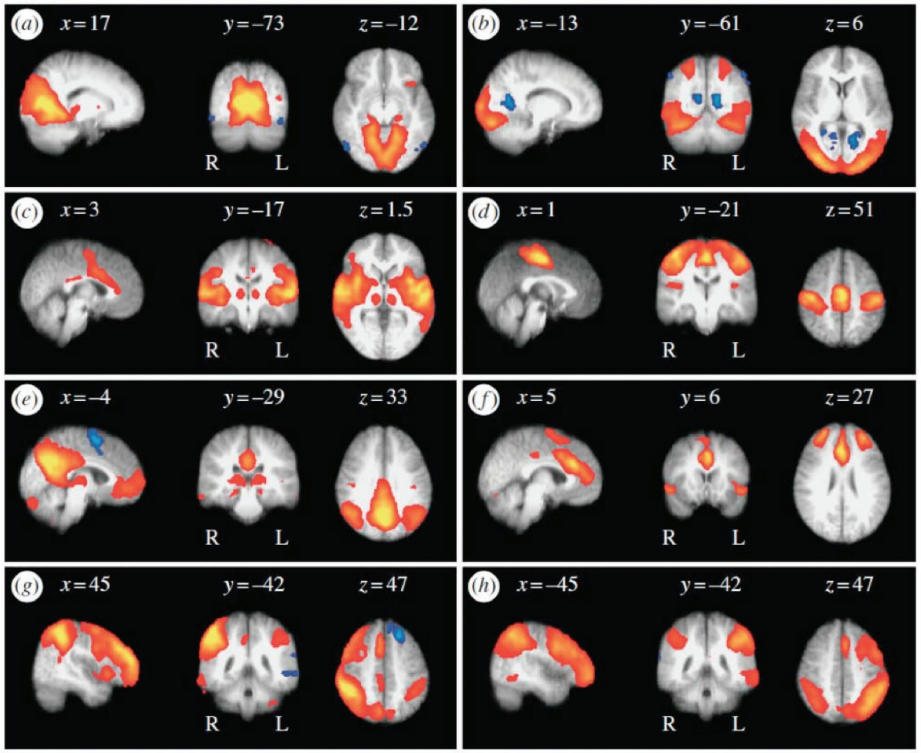


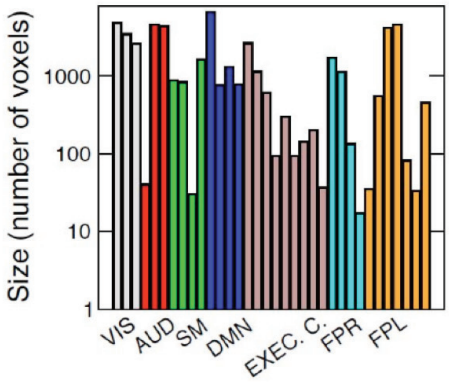
The "top 10 bands"

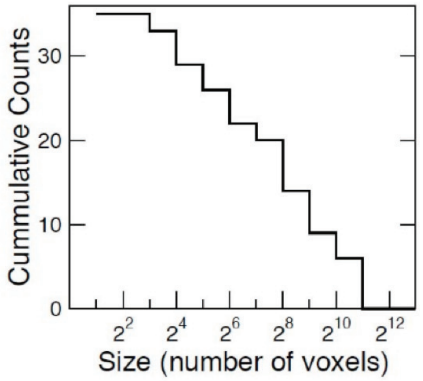


Here we choose the eight most relevant

split into 35 clusters



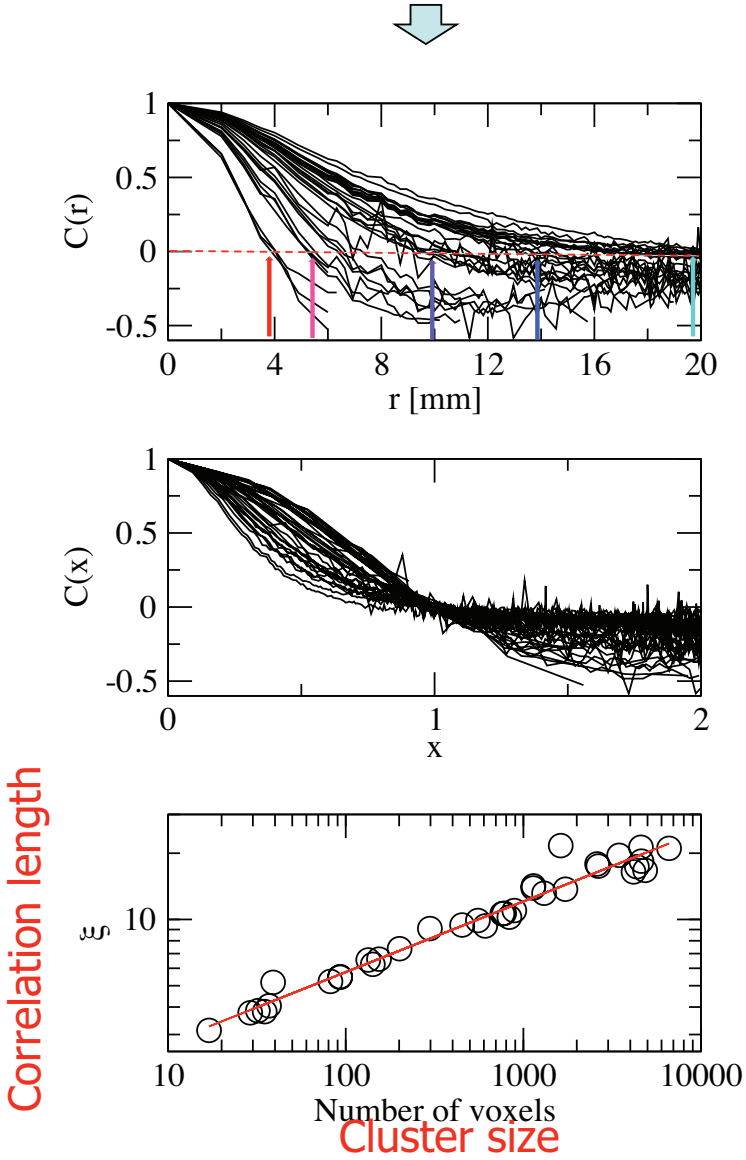




Eight PICA-estimated resting patterns estimated from a group of subjects.

Left panels shows the saggital, coronal and axial views for each map. Right panels depict the size of each of 35 clusters (a.k.a "blob") analyzed (top) and its distribution.

We compute the cross-correlation of the BOLD time series as a function of distance



Correlation length diverges with cluster size

Big, intermediate and small “blobs” behaves all in the same way

The bottom line: Two voxels 4 mm appart on a blob of 20 voxels are as correlated as those 40 mm appart on a blob of 4000 voxels

BlahBlahlogy

1) Functional correlations in cortical fMRI time series are scale-free and comparable with those seen near at a critical point in the Ising model.

2) Correlation/anticorrelation ratios ~ 1 (i.e., zero magnetization) only in healthy brains.

3) Correlations diverges with size -> implies criticality

4) Neuronal avalanches as "homeostatic" cortical states, also seen in awake freely behaving animals.

5) Motion (behavior) is scale free over orders of magnitude (inactivity) and it should be the expresion of criticality as well.

5) Theory, Theory, Theory is needed!!

Reading

Articles:

»*Eguiluz V, Chialvo DR, Cecchi G, Baliki M, AV Apkarian*. Scale-free brain functional networks. Phys. Rev. Letters 92, 018102 (2005).

»*Chialvo DR*. Critical brain networks. Physica A, 340,4,756-765 (2004).

»*Beggs J. & Plenz D*, Neuronal Avalanches in Neocortical Circuits J. of Neuroscience, 3 23 (2003).

»*Chialvo DR.* Are our senses critical? Nature Phys. 2006

»*Copelli M & Kinouchi O*. Optimal dynamical range of excitable networks at criticality, Nature Phys. (2006).

»*Chialvo DR*. The brain at the edge (arxiv.org/ q-bio.NC/0610041)

»*Chialvo DR.* Emergent complexity: what uphill analysis or downhill invention can not do. New Ideas in Psychology, (2008).

»*Chialvo DR.* Beyond feeling: chronic pain hurts the brain disrupting the default-mode network dynamics, J. of Neuroscience, (2008).

»Chialvo DR, Balenzuela P, Fraiman D. The brain: What is crtitical about it? (arXiv.org/ cond-mat/ 0804.0032)

»Fraiman D, Balenzuela P, Foss J. Chialvo DR, Ising-like dynamics in large-scale brain networks. (arXiv.org/ cond-mat/0811.3721)

»Plenz & Chialvo, arxiv.org/abs/0912.5369, submitted 2010)

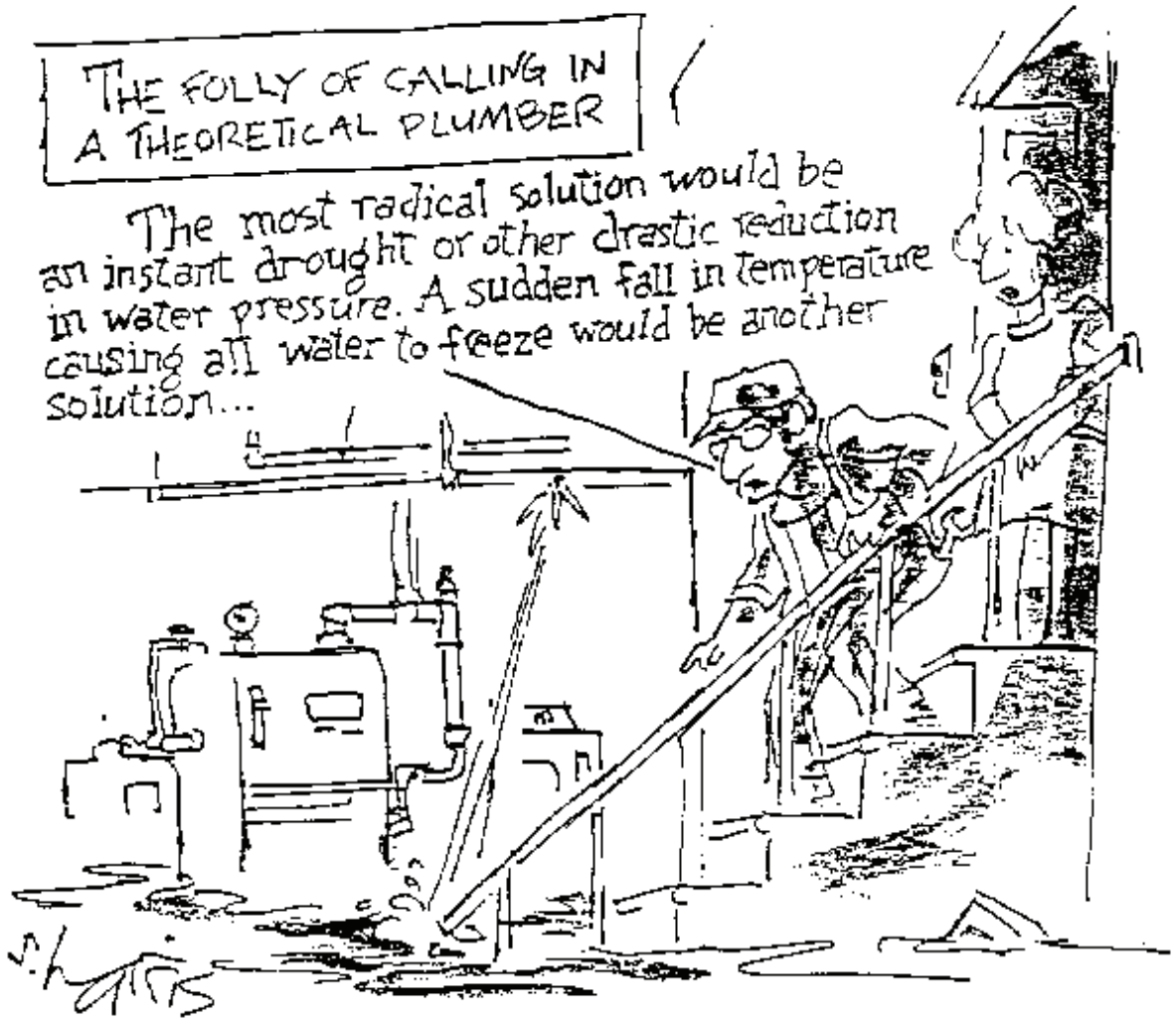
Review:

»*Sporns O, Chialvo DR, Kaiser M, and Hilgetag CC.* Organization, Development and Function of Complex Brain Networks. Trends in Cognitive Sciences, 8 (9): 387-(2004).

Books:

»How Nature Works. (Per Bak); Things that think. (Chialvo, 2009?)

Theoretical plumber:
in biology be carefull what you ask for

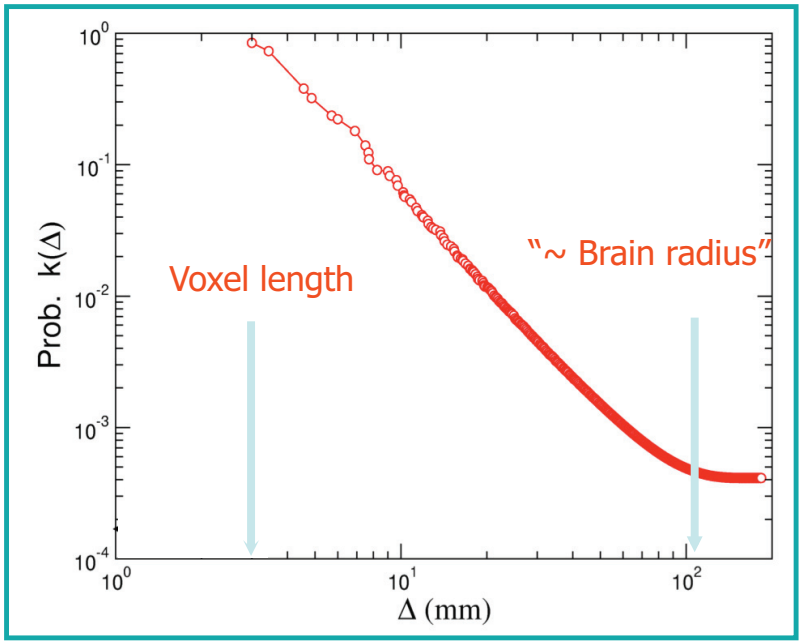


fMRI

Average Functional Links Length Distribution

Probability of finding a "link" between two nodes separated by a distance $x < \Delta$

$$k(\Delta) \sim 1/x^2$$



From Eguiluz et al, Phys. Rev. Letters (2005).

Critical Ising networks ~ brain networks